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Iowa Engineering Experiment Station
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U. S. Public Health Service
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DESIGN REQUIREMENTS FOR MUNICIPAL DIATOMITE FILTERS

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Second Progress Report
July 1, 1962 through February 29, 1964
(20 months)

Iowa State University of Science and Technology
Engineering Experiment Station
Ames, Iowa

April 30, 1964

Summary Statement

DESIGN REQUIREMENTS FOR MUNICIPAL DIATOMITE FILTERS

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Iowa Engineering Experiment Station
Department of Civil Engineering
Ames, Iowa
April 30, 1964

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INTRODUCTION

Since 1958, one of the main research activities of the Sanitary Engineering Section of the Department of Civil Engineering and the Engineering Experiment Station of Iowa State University has been the study of the process of filtration of water. All of the studies completed, in progress, or in the planning stage have been concerned with one basic question: "How can a filter be designed, constructed, and operated to provide filtered water of the desired quality at least cost?"

Few filters are now designed on an orderly scientific basis to provide water of the desired quality at the least cost. Instead, a filter is usually designed on the basis of "past experience" to provide water of the desired quality at a cost which the consumer is willing to pay. The primary objective of the research at Iowa State is to hasten the change from the "art" to the "science" by contributing to the knowlege of water filter design.

To contribute to this knowledge, it is necessary to determine on a scientific basis:

1. How a given particle in suspension is removed by a filter,
2. What factors affect the design and operation of a filter, and
3. How these factors affect the economy of filter operation.

Studies are now being conducted with both sand and diatomite filters to secure information which can be applied in the design of both types of filters. Work in the area of diatomite filtration was initiated in 1958 with support from a Research Grant (RG-5958A) under the Public Health Service Small Grant Program. Pilot filtration equipment was developed and verified in laboratory tests. In 1960, the current program of research was undertaken with a three-year Research Grant (WP-00196) from the Division of Water Supply and Pollution Control, Public Health Service. The first PROGRESS REPORT, covering the first 23 months of the study, was issued on September 1, 1962. The Research Grant was recommended for continued support for an additional three years. This additional report covers the research conducted during the period from September 1, 1962 through April 30, 1964 under Research Grants WP-00196-03 and WP-00196-04.

Work was initiated in the area of sand filtration in 1959 with support from the Engineering Experiment Station and from Research Grant RG-6755A under the PHS Small Grant Program. These studies were undertaken to provide filtration experience with sand filters under conditions similar to those under which the diatomite filters were being operated. The studies proved to be so helpful in explaining how a given particle is removed by a filter that they have been continued with Experiment Station support. One paper resulting from these studies -- "Selection of Sand Filtration Rates" - was awarded the Publications Award for 1962 by the American Water Works Association "for the most notable contribution to the science of public water supply development published by the Association."

DIATOMITE FILTRATION

Method of Approach:

The specific aims of the studies being conducted under Research Grant WP-00196 are as follows:

1. To determine the optimum diatomite filter design requirements for the economical filtration of raw and chemically treated water for municipal use.

2. To determine the characteristics of municipal applications in which diatomite filters may be successfully and economically used.

3. To determine the extent to which the chemical quality of water and the amount and kind of diatomite being used affect the removal of solids on diatomite filters.

To accomplish these objectives, the overall study has been broken down into distinct sub-areas and topics which have been assigned to personnel for study and report. The research results are ultimately made available in the following forms:

1. M.S. or Ph.D. theses submitted by a graduate student in partial fulfillment of the requirements for the degree. The theses will include all of the pertinent data collected during the study. Reproductions of the Ph.D. theses are available in microfilm or Xerox copies from University Microfilms, Ann Arbor, Michigan, and reproduction of copies of M.S. theses can be secured from the Iowa State University Library.

2. PROGRESS REPORTS to the Division of Water Supply and Pollution Control. As soon as one phase of the study is completed, a Progress Report is prepared which includes all of the detail and data necessary to support the conclusions drawn.

3. A condensed manuscript of each phase of the study suitable for publication. When a phase of the study is completed to such a degree that the information should receive more widespread dissemination than is available through theses or Progress Reports, a manuscript is prepared and submitted for publication to the most appropriate Journal.

A total of ten theses on the subject of diatomite filtration and six on the subject of sand filtration have been completed since 1959. Eleven papers on diatomite filtration and six papers on sand filtration have been published since 1960. In addition fourteen papers on filtration have been presented since 1960 by professional personnel associated with this project before technical and professional organizations.

To accomplish the objectives of Research Grant WP-00196, the first studies were designed to provide experience with the effect of terminal head loss, flow rate, body feed rate, filter aid grade, water quality, water temperature, and a number of other variables on diatomite filter operation. Several laboratory and pilot filters were constructed, modified, and operated in more than 500 filtration tests. These data are available in a doctoral thesis, DESIGN OF MUNICIPAL DIATOMITE FILTERS FOR IRON REMOVAL, 1961, Robert L. LaFrenz; and the data were used as the basis for three sections of the First Progress Report (September 1, 1962):

I. Optimums in Diatomite Filtration
II. A Theory of Diatomite Filtration
III. Optimum Economical Design for Municipal Diatomite Filtration Plants

All of these sections have subsequently been published in the JOURNAL of the American Water Works Association.

A theory of filtration was developed which made it possible to predict the head loss which would be observed under a wide variety of conditions during diatomite filtration if two filter cake permeability characteristicc could be determined:

K_3, a measure of the impermeability of the filter aid used for precoat, and

K_4, a measure of the impermeability of the suspended solids-body feed portion of the filter cake

During the period covered by the SECOND PROGRESS REPORT, studies were undertaken to evaluate the factors which affect the K_3 values of and the removal of suspended solids by filter aids used in water filtration. These studies include:

1. Hydraulic and particle size characteristics of some diatomite filter aids - Aim 3. (J. H. Dillingham and E. R. Baumann) Completed

2. Effect of ions in solution on the permeability of diatomite filter aids - Aim 3 (M.S. Abdulrahman and E. R. Baumann) Completed

3. Streaming potentials in diatomite filtration of water - Aim 3. (C. S. Oulman and E. R. Baumann) Completed

4. Coatings for filter media - Aim 3 (C. S. Oulman, Donald Burns, E. R. Baumann) In Progress

5. Removal of particulate matter on coated filter media - Aim 3 (C. S. Oulman, Donald Burns, E. R. Baumann) In Progress

As a result of recent observations these studies should be expanded to determine the effect of current filter aid handling and feeding practices on the degradation of filter aid particles. (Future)

To determine the characteristics of municipal applications in which diatomite filters may be successfully applied, a number of studies were undertaken to determine the impermeability (K_4) of various filter cakes typical of those in municipal installations. These are:

1. Permeability of filter cakes containing various grades of diatomite and flocculent iron oxide - Aim 2 and 3. (J. L. Cleasby, E. R. Baumann) Complete

2. Permeability of filter cakes containing various flocculent solids - Aim 2. (J. L. Cleasby, E. R. Baumann) Complete

3. Permeability of filter cakes containing various grades of diatomite and various types of clay colloids such as kaolinite and montmorillonite - Aim 2 and 3. (J. L. Cleasby, E. R. Baumann, P. Regunathan) In Progress

4. Permeability of filter cakes containing natural suspended solids in surface waters - Aim 2 (J. L. Cleasby, E. R. Baumann, P. Regunathan. (To be initiated in Summer of 1964)

5. Permeability of filter cakes containing solids from the lime-soda softening process - Aim 2. (E. R. Baumann and James H. Dillingham) (To be initiated in Summer of 1964)

6. Permeability of filter cakes containing solids resulting from the chemical treatment of surface waters - Aim 2. (E. R. Baumann, J. L. Cleasby, C. S. Oulman) (To be initiated in Summer and Fall of 1964)

The results of these studies will provide the data necessary for determining the optimum design characteristics and costs for diatomite filtration plants for the treatment of each type of water. To reduce the time required for determining "least cost" design requirements (Part III, First Progress Report), a computer program is now being prepared for use with an IBM 7074-1401 Computer:

1. Computer Applications in Water Filtration Plant Design - Aim 1. (J. H. Dillingham, J. L. Cleasby and E. R. Baumann) (In Progress)

This computer program will be used during 1965 with cost and filter cake permeability data collected in 1964 and 1965 to determine the diatomite filter design for the most economical filtration of raw and chemically treated water at different types of installations suitable for municipal use.

Abstracts of Completed Studies:

1. EFFECTS OF VARIOUS VARIABLES ON DIATOMITE FILTER OPERATION (LaFrenz, Robert L.)DESIGN OF MUNICIPAL DIATOMITE FILTERS FOR IRON REMOVAL. Ph.D. thesis. Iowa State University Library, 1961. (See also FIRST PROGRESS REPORT, Parts 1, 2, and 3.)

Diatomite filtration for municipal potable water supplies has not developed as rapidly as expected, principally due to setbacks in its early municipal application. The early failures can be traced to a lack of understanding of the basic principles affecting diatomite filtration. A better understanding of some of these factors was presented by Baumann in 1954. Several other investigators have conducted research on the subject, but in general, considerable work still remains before the process can be understood completely and can be applied under all conditions.

The objective of this study was basically twofold: to develop a better understanding of the fundamentals and theory of diatomite filtration, and to apply these fundamentals to the design of a municipal diatomite filter so that optimum conditions are obtained. For these purposes, three filters were utilized, a constant rate pressure filter in the form of a pilot plant, a variable head constant rate permeameter or miniature pressure filter, and a constant head permeameter or constant head pressure filter. Water to be filtered was Iowa State University tap water to which ferrous sulfate was added. The mixture was then aerated to convert the iron to an insoluble precipitate. Three concentrations of iron were used;

7-8 mg/l, 4 mg/l, and 2 mg/l. Copper sulfate was added in some runs to aid in converting the ferrous iron. One test series was conducted on the pilot plant to determine the shape of the curves of head loss versus total gallons of filtrate for runs conducted to a high head loss. The series conducted with the constant head filter was used to demonstrate a method of relating results from constant head filtration to results obtained from constant rate filtration. A series of runs was conducted at each of three different rates and with three different waters to determine the effect of filtration rate and iron concentration on the optimum conditions for filtration.

From the results of this study a mathematical theory of diatomite filtration was developed. By the use of the theory, four or five runs are sufficient to develop the straight line curves of head loss versus time for any filtration rate, iron concentration, and body feed.

The three optimum body feeds which occur in diatomite filtration were studied and explained. The diatomite economy optimum body feed is the body feed which produces the maximum number of gallons of filtrate per lb of diatomite. For a given water and filter aid, it is a function of the terminal head loss and the amount of precoat used. The optimum body-feed in terms of hydraulics is the body feed which produces the most filtrate per unit area when water is filtered until some given terminal head loss is reached. It is normally a very high body feed. The overall optimum body feed is that body feed which produces potable water at the minimum cost per gallon, considering all cost factors.

A procedure is developed for determining the overall optimum body feed, the optimum terminal head loss and the optimum filtration rate for a municipal plant. These optimums depend on the cost of diatomite, labor, power, and equipment. The optimum conditions for the water used in this study occurred for the lowest body feed which gave a straight line head loss versus time realtionship, at a relatively high head loss, and at a low rate of filtration.

2. THEORETICAL ASPECTS OF DIATOMITE FILRATION
(See Part I, SECOND PROGRESS REPORT, Attached)

In January, 1964, a paper which interpreted in non-technical language current knowledge affecting diatomite filter operation and design was presented at the 1964 Convention-Exposition of the National Swimming Pool Institute. In this paper the need for further information now being gathered for use in filter design was discussed.

3. MODIFIED FORM OF DIATOMITE FILTRATION EQUATION
(See Part II, SECOND PROGRESS REPORT, Attached)

The equation for constant rate filtration developed in this study involved two terms, K_3 and K_4, related to the permeability of the filter cake. These terms are, in reality, variables which are functions of the absolute viscosity, and specific weight of the water, the gravitational constant, and the average specific resistances, α_1 and α_2, of the precoat and body feed portions of the filter cake. A modified form of the original filtration equation is presented in which these new variables can be used to account for temperature effects. K_3 and K_4 values were temperature dependent, but values of α_1 and α_2 are true constants.

4. HYDRAULIC AND PARTICLE SIZE CHARACTERISTICS OF SOME DIATOMITE FILTER AIDS
(See Part III, SECOND PROGRESS REPORT, Attached; also, Dillingham, James H. HYDRAULIC AND PARTICLE SIZE CHARACTERISTICS OF SOME DIATOMITE FILTER AIDS, M.S. thesis, Iowa State University Library, 1963.)

Specifications for the desirable characteristics of filter aids become necessary as the use of diatomite filtration for the production of potable water increases. A filter aid specification should include standardized methods to be used in determining the characteristics of the filter aid. A standard method must be relatively inexpensive and simple to perform and must give consistent, reproducible results.

Two modified ASTM methods for determining particles size and a method for determining a characteristic of permeability (K_3) by use of a small pressure filter (EK filter) were investigated in this study for possible use in a filter aid specification. The results indicate that the ASTM D422-61T method of particle size analysis, as used in this study, and the procedure used to determine K_3 values meet these requirements and would be suitable for use in filter aid specifications.

Particle size distributions were determined for each of 19 commercial grades of filter aids. K_3 values were also determined for most of the filter aid grades.

The following conclusions were drawn from the results of this investigation:

a. The ASTM methods, D422-39 and D422-61T are equally repeatable. The -61T test was used for most of the particle size tests made in this study because the dispersing agent was easier to prepare.

b. The composite correction method for correcting hydrometer readings simplifies the test procedure and is adequate when temperature variations are small.

c. The particle size results obtained when using 50 gm samples are slightly finer than corresponding results obtained when using either 30 or 20 gm samples. This is probably due to greater particle size degradation from the air dispersion tube and more hindered settling. There is more chance for particle collision when using 50 gm samples.

d. More effective particle dispersion is realized in the -61T test. The more effective dispersion probably results from the greater quantity of dispersing agent used in the -61T test.

e. The -61T test, as modified in this study for application to diatomite filter aids, gives consistent, repeatable results.

f. K_3 results obtained are repeatable when precautions are taken to insure that the apparatus is clean. Repeatability should improve with the proposed revisions of apparatus.

g. The presence of minerals, including polyelectrolytes, in the water being filtered may affect the K_3 value of the filter aid. It was found that the system had to be cleaned thoroughly to obtain repeatable K_3 results.

h. The significant decrease in K_3 which resulted after the precoat pot was added indicates that diatomite filter aid particles are degraded when they pass through a pump. Other types of equipment such as feeders, mixers, ejecters, etc, may also degrade filter aid particles.

i. K_3 depends not only on the particle size distribution of the filter aid, but also on other characteristics of the filter aid.

j. There has been and may continue to be considerable variation in the hydraulic characteristics of a given commercial grade of filter aid between different shipments. In some cases, this variation may result in the overlapping of the hydraulic characteristics of two normally different grades of filter aid.

5. EFFECT OF IONS IN SOLUTION ON THE PERMEABILITY OF DIATOMITE FILTER AIDS (A PROGRESS REPORT is being prepared.) Abdulrahman, M.S. EFFECT OF IONS IN SOLUTION ON THE PERMEABILITY OF DIATOMITE FILTER AIDS. Ph.D. thesis. Iowa State University Library, 1964.)

As a result of the difficulty in obtaining a reproducible measure of filter cake permeability at two different geographic locations in the previous study, this study was undertaken to evaluate the effect of ions in solution of cake permeability. Permeability is a measure of the ability of a layer of porous material such as diatomite or soil to transmit a liquid under the influence of a pressure differential. In this study, the permeability of a filter aid was measured by determining the rate of flow through a fixed area of filter cake containing a fixed weight of filter aid under constant head conditions and by using a special K_3 filter developed for use in determining the permeability of filter aids. Use of the K_3 filter with the same sample of filter aid at other locations using different waters did not produce similar permeability results. However, the results using any specific water were reproducible. Since the only variable involved appeared to be in the dissolved mineral matter in the test water, the question was raised as to whether such variations could significantly affect filter cake permeability.

The purpose of this study, therefore, was to investigate the effect which cations and anions composing the dissolved solids in water have on the permeability of a diatomite filter cake and to explain the mechanism behind their effect. The study was designed to evaluate the effect of several cations and anions in true solution on the permeability of the commercial diatomite filter aid, Celite-535.

The permeability was expressed in terms of its K_3 impermeability coefficient as proposed in a recently develped diatomite filtration equation(Part II, First Progress Report)

It was found that some chemicals in solution, such as $AlCl_3$, $Al_2(SO_4)_3$ and $FeCl_3$, increased the permeability of the filter aid or decreased the K_3 values from those obtained using distilled water. Another group of chemicals in solution, $CaCl_2$, Na_2SO_4, KOH, $MgSO_4$, decreased the permeability of the filter aid or increased the K_3 values from those obtained using distilled water under identical conditions.

These effects of the salts in solution on filter cake permeability can be explained on the basis of the formation of the hydrate envelope around diatomite particles. The hydrate envelope refers to the layer of oriented molecules of water next to the diatomite particles; there is a firmly bound layer of adsorptional water around the diatomite particle and a diffuse layer of loosely bound water. The degree of hydration of the diatomite particles, or the amount of bound water associated with the diatomite particle, depends on the magnitude of the particle charge, on the condition of the particle surface and also on the nature and properties of the adsorbed ions. In general, it was found that, as the valency of the cation becomes greater, the diffusional layer is compressed, and the size of the hydration envelope decreases, providing more pore space available for flow.

We can conclude, therefore, that the different salt concentrations will result in the retention of different thicknesses of the bound water layer around the diatomite particles in the filter cake. The cations and anions will increase the K_3 of a filter cake due to changes in pore space available for flow in the following order (K_3 values from lowest to the highest): Cation order, $Al^{+++} < Fe^{+++} < H^+ < Ca^{++} < Na^+ < K^+$ and Anion order, $Cl^- < HCO_3^- < SO_4^{--} < CO_3^{--} < OH^-$.

6. STREAMING POTENTIALS IN DIATOMITE FILTRATION OF WATER
(See Part IV, SECOND PROGRESS REPORT, Attached; also,
Oulman, C. S. STREAMING POTENTIALS IN DIATOMITE FILTRATION
OF WATER, Ph.D. thesis. Iowa State University Library, 1963.)

Most particulate matter has a negative electrical surfact charge when in contact with water. Suspended solids in water,therefore, tend to resist being brought into contact with and being adsorbed on the particles of a filter media because both are negatively charged and tend to repel each other. Some ions in water, however, are adsorbed on the surface of the particles and tend to change the net charge of the particles. The amount of repulsive force depends therefore on the net charge of the particle and its adsorbed ions.

The electrical surface charge of a particle is related in sign to its zeta potential, which can be determined from streaming potential measurements. Streaming potentials are electrical potentials that are generated when water is filtered through a porous media. In this study, streaming potentials were measured to determine the zeta potential of diatomite filter media which was in contact with water containing different kinds of cations. The apparatus and techniques used for streaming potential measurements are described in detail.

It was found that sodium ions did not affect the zeta potential of the diatomite filter media, magnesium ions reduced the zeta potential somewhat and ferrous ions lowered the zeta potential to zero. Aluminum and ferric ions reversed the zeta potential from negative to positive, as did a cationic organic polyelectrolyte.

By neutralizing the surface charge or reversing its sign, ferrous, ferric, aluminum compounds and cationic polyelectrolytes when adsorbed on the particles of a filter media should aid in removing fine particulate matter from water because they tend to eliminate the inter-particle repulsive forces, and should tend to promote adsorption of suspended solids on the particles of the filter media.

7. COATINGS FOR FILTER MEDIA

(See Part V, SECOND PROGRESS REPORT, a preliminary report to introduce the subject. A complete progress report is being prepared)

Some of the suspended solids removed from water by filtration are too small to have been mechanically strained out in the openings of the filter media. These solids are thought to be removed by a combination of adsorption and electrical effects. The surfaces of filter media such as sand or diatomite are not particularly adsorptive. Furthermore, in water these filter media have negative electrical surface charges just as the suspended solids do. Inter-particle repulsive forces tend to prevent these particles from coming into close contact, a condition necessary for promoting adsorption.

Research by others has shown that the adsorptive properties of filter media can be improved by admixing them with coagulants such as alum or ferric salts which form coatings on the particles of the filter media in water. Removal of color, turbidity, and bacteria is markedly improved by filtering water through media that has been so coated.

Research by the authors has shown that filter media coated with coagulants have a positive zeta potential, as determined by streaming potential measurements. Studies are being made to determine the properties of diatomite filter media that have been treated with organic cationic polyelectrolytes. Previous work by the authors showed that one polyelectrolyte reversed the zeta potential of diatomite to a positive value.

Three polyelectrolytes have been tested for use in coating diatomite. Two reversed the zeta potential to a high positive value; one reduced the zeta potential to a low negative value. Of the two that reversed the zeta potential, one made the filter cake relatively impermeable, but the other did not affect the filter cake permeability significantly. It was also found that the zeta potential depends on the pH of the water being filtered. At pH values of 8.5 and above, the zeta potential could not be made positive with the polyelectrolyte that did not affect the permeability.

Further studies will be made to evaluate other polyelectrolytes which will form electropositive coatings on diatomite filter media without adversely affecting its hydraulic characteristics. These coatings for filter media should be valuable for the filtration of water because course coated filter media on which suspended solids can be adsorbed can be used where non-coated fine filter media are currently needed to remove particles by mechanical straining. This should lead to lower power costs and longer filter runs.

8. PERMEABILITY OF FILTER CAKES CONTAINING VARIOUS FLOCCULENT SOLIDS (See Part VI SECOND PROGRESS REPORT, Attached; and also Hall, Bruce B. PERMEABILITY OF VARIOUS GRADES OF DIATOMITE FILTER CAKE CONTAINING FLOCCULENT IRON OXIDE. M.S. thesis. Iowa State University Library, 1964, also Hawley, James F. PERMEABILITY OF DIATOMITE FILTER CAKES CONTAINING VARIOUS FLOCCULENT SOLIDS. M.S. thesis. Iowa State University Library, 1964.)

There are many natural iron bearing ground waters. The various waters have different filtering characteristics in a diatomite filter. This study explored some possible reasons for these differences. A pilot pressure diatomite filter was operated on laboratory prepared synthetic waters to determine the effect of three variables on the permeability of the resulting filter cake.

a. Two different body feed techniques were studied to determine their effect on cake permeability and effluent quality. One technique involved feeding diatomite into the raw water tank while the suspended floc was forming. The other involved feeding body feed into the filter influent line after the floc particles had formed.

b. Several different salts of iron and aluminum were used to prepare flocculent solids which were filtered to determine the effect of different suspended solids on both cake permeability and effluent quality.

c. Several different commercial grades of diatomaceous earth were used as filter aid when filtering a single type of flocculent solid to determine the effect of diatomite grade on cake permeability and effluent quality.

A measure of filter cake impermeability was obtained by calculating K_4 values using the diatomite filtration equation. A series of at least seven runs was made with suspended solids obtained from five different chemicals: ferrous sulfate, ferrous chloride, ferric chloride, ferric sulfate, and aluminum sulfate. At least three runs were conducted with each chemical using the second body feed method and a single body feed rate to determine the reproducibility of the data. One run was made using the first body feed method described above, and three runs were made at various other body feed rates. Microscopic examination and zeta potential measurements of the suspended solids were made.

Many different grades of diatomite are marketed by various manufacturers. The difference between grades in mean pore size influences both the impermeability of the filter cake and the clarity of the filter effluent when used in water filtration. The filter aids used in this study were Celite 545, Celite 535, Celite 503, and Hyflo Super-Cal. At least seven filter runs were conducted with each grade to obtain data about the relationship between head loss through the filter cake and the volume of filtrate.

The factor that was varied between runs with each grade was the rate of body feed. The rate of filtration, precoat quantity, suspended solid concentration, copper concentration, water source, raw water temperature, and raw water pH were essentially constant during all filter runs.

As a result of this study, the following conclusions were drawn:

a. There was no apparent difference in the filter cake permeability caused by the two different body feed techniques regardless of the source of the suspended solids.

b. Significant difference in filter cake permeability was discovered for water containing suspended solids from different chemical sources. Impermeability values (K_4) obtained for raw water containing suspended solids from trivalent iron and aluminum salts were approximately ten times as great as the K_4 values for cakes containing solids resulting from use of the bivalent iron salts.

c. Microscopic examination of the flocculent solids showed that the particle size of floc from trivalent iron salts was considerably larger than the floc from bivalent iron salts. The larger particles were approximately the size of filter aid particles.

d. Examination of the chemical solution used to prepare the artificial raw water showed that the trivalent salts precipitate and form minute particles in the chemical bottle. The particles are presumed to be colloidal, since they do not settle in the bottle. The bivalent salts precipitate much less noticeably in the bottle. This precipitation may contribute to the formation of the larger floc particles in the raw water.

e. When the solution of the bivalent salts was oxidized to the trivalent state with potassium dichromate, the K_4 values obtained were close to the values obtained with the trivalent iron salts. The oxidation state of the cation is in some way responsible for the floc particle size in the raw water.

f. The grade of diatomite used as body feed affects the impermeability of the resulting filter cake. At the same body feed rate, the finer grades of diatomite produce a filter cake with a slightly higher impermeability value (K_4) in the filtration of a flocculent solid. The percentage of change in the impermeability of the body feed layer (K_4) was not as great as the corresponding percentage of change in impermeability of the clean diatomite (K_3). For example, an increase of 450 percent in K_3 resulted in an increase of 48 percent in K_4 when the suspended solids-to-body feed ratio was 0.09. When this ratio was 0.07, the corresponding increase in K_4 was only 55 percent.

However, these changes in K_4 represent major changes in the length of filter run terminated at any given total head loss. The relatively coarse Celite 545 would produce a run length about 33 percent longer than the fine Hyflo Super-Cel for this water. This benefit can be obtained for 12 percent increase in diatomite cost at current prices.

g. The exponential relationship between the impermeability (K_4) and the ratio of the concentration of suspended solid to concentration of body feed was demonstrated for all of the grades of diatomite studied and all of the different suspended flocculent solids. In the general exponential equation, $K_4 = ax^b$, where x is the ratio of concentration of suspended solid to concentration of body feed, exponent b was approximately 2 for all the grades and solids studied.

h. There was no appreciable change in effluent clarity between the coarser and finer grades of diatomite or for the various flocculent solids filtered. Effluent iron or aluminum concentrations did not exceed 0.3 ppm in any of the filter runs.

SAND FILTRATION

Method of Approach:

The specific aims of the studies conducted in the area of sand filtration are as follows:

a. to determine whether the factors affecting sand filter operation are related so that sand filter design can be approached on the basis of producing water of the required quality at least cost.

b. to determine how the operation of sand filters can be improved by modification of current design and/or operating practice.

c. to determine the extent to which the chemical quality of the water and suspended solids affect the removal of solids on sand filters.

d. to determine whether artificial methods (coatings) can be used to improve the adsorption removal of sand filters.

To achieve these aims, the first studies were designed to provide a wide variety of operating experience with sand filters. Accordingly, with support from P.H.S. Research Grant RG-6755A under the Small Grant Program, a laboratory pilot sand filter apparatus was constructed and has been operated in over 250 runs. These runs have involved filtration of laboratory prepared waters, lime-soda softened waters resulting from full-plant treatment, and iron-bearing waters from deep wells. The pilot plant consists of three separate sand filters equipped with rate controllers, automatic turbidity recorders, and numerous water sampling points throughout the sand filter bed.

The various studies completed to date include the following:

1. Selection of sand filtration rates for sand filters - Aim 1,2
   (J. L. Cleasby and E. R. Baumann)
2. Iron removal vs. depth in a sand filter - Aim 1,3
   (J. L. Cleasby and H. Munson)
3. Effect of rate disturbances on the quality of filtered water - Aim 2,3
   (J. L. Cleasby, M. M. Williamson, E. R. Baumann)

4. Evaluation of granular filters for contact water softening - Aim 3,4
   (J. L. Cleasby, Norman Wenck)

5. The effect of backwash techniques on effluent quality from sand filters Aim 2
   (R. L. Johnson and J. L. Cleasby)

Abstracts of Completed Studies:

1. SELECTION OF OPTIMUM FILTRATION RATES FOR SAND FILTERS, (Cleasby, John L. Ph.D. thesis, Iowa State University Library, 1960. Also Cleasby, J. L. and E. R. Baumann, SELECTION OF OPTIMUM FILTRATION RATES FOR SAND FILTERS, Iowa Engineering Experiment Station BULLETIN 198, 1962., Also Cleasby, J. L. and E. R. Baumann, SELECTION OF SAND FILTRATION RATES, Journal AWWA, 54:5, p 579-602, May, 1962.)

The filtration of water containing particulate matter in suspension was studied on three graded sand filters. The filters were 6 in. ID with a sand depth of 30 in. and a sand effective size of 0.55 mm. Two types of suspensions were studied both of which are typical of waters encountered in municipal practice. One was a well water containing 7 to 9 mg/l of iron which was aerated and mixed to cause the precipitation of the iron in the form of hydrous ferric oxide particles 1 to 20μ in size. The other was the filter influent water of a split-treatment lime-soda ash softening plant which contained precipitated calcium carbonate particles 1 to 10μ in size. Effluent quality from each filter was monitored by a precise continuous reading photoelectric turbidimeter.

The filters were operated simultaneously at different constant filtration rates between 0.7 and 8 gpm/sq ft with the objective of determining the optimum rate of filtration from the standpoint of the maximum volume of acceptable water produced per filter run to a given terminal total head loss.

When filtering suspensions which caused head loss to develop at an increased rate as the filter run progressed, greater production occurred at higher filtration rates. An optimum rate was reached in some cases beyond which further rate increases resulted in reduced production. The optimum rate based solely on production considerations was identified as the lowest rate which resulted in the development of head loss in nearly a linear manner. Filtrate quality was not always acceptable at the optimum rate, and therefore water quality must also be considered in selecting the operating filtration rate.

No optimum rate tendency was observed during the filtering of suspensions characterized by linear head loss development at all rates. Higher rates resulted in reduced production to a given terminal head loss.

The reason for the optimum rate tendency was found to be the formation of a compressible surface cake by that portion of the particles removed from suspension on the sand surface. Head loss in the surface cake developed in an exponential manner; head loss below the surface cake developed in nearly a linear manner.

Various other phases related to the sand filtration of water were studied: (1) The relation between filtrate quality and depth at different rates and at different times during a filter run. (2) The relation between initial filtrate quality and rate of filtration. (3) The behavior of filtrate quality at different filtration rates at the beginning of a filter run. (4) The behavior of effluent quality following a sudden rate increase on a partially dirty filter. (5) The relative merits of constant rate, constant pressure, and variable rate filtration.

2. IRON REMOVAL VS. DEPTH IN A SAND FILTER
(Munson, Hugh. M.S. thesis, Iowa State
University Library, 1961.)

A number of attempts have been made to formulate an expression that will permit the prediction of the performance of sand filters for water supplies. The earliest of these attempts (1937) assumed that for a clean filter, a first order relation was between the removal of suspended solids and the amount of solids in the water being filtered ($\frac{dI}{dL} = -\lambda I$ where I is the concentration of suspended matter in the water and L is the depth of the filter.) Later attempts have refined the early equations, but the first order assumption for the clean filter has always been accepted without experimental proof for a uniform sand size and homogeneous suspension.

This study was conducted to try to prove that this relationship is valid for a clean sand filter. A pilot rapid sand filter plant was used to filter a water containing hydrous ferric oxide floc particles. The water was prepared by adding ferrous sulfate to University tap water followed by aeration and mixing. The filter was equipped so that samples could be withdrawn at increments of depth throughout the entire filter depth. The sand was essentially uniform lying between adjacent standard U.S. sieve sizes (20 and 30 mesh).

The data collected in this study did not support the first order relation assumed by other investigators. The possible reasons for the lack of support are that the suspension is non homogeneous and the sand is not strictly uniform. It was not possible to say which of these two factors was the most important in causing the non conformance with the first order relation.

3. EFFECT OF RATE OF FLOW DISTURBANCES ON THE QUALITY OF FILTERED WATER (Williamson, M.S. thesis, Iowa State University Library, 1962. Also Cleasby, J. L., Williamson, M. M., and E. R. Baumann. EFFECT OF FILTRATION RATE CHANGES ON QUALITY. Journal A.W.W.A., 55: 7, p 869-880, July, 1963.)

Many current water treatment plant practices result in the possibility that the filtration rate may be increased from 50 to 100 per cent on a dirty filter in a very short time. The effect of such changes on filtered water quality has been noticed by several investigators. However, no attempt has been made to study this phenomena quantitatively. This study was conducted to determine the relation between the magnitude, duration, and speed of the rate change and the resulting effect on effluent quality.

The investigations included both pilot scale and plant scale studies. Three types of suspended matter in the water were investigated.

The following conclusions resulted:

a. Rate of flow increases on a partially dirty filter cause part of the material deposited in the filter to be flushed through the filter into the effluent.

b. The larger the rate of flow increase the greater the detriment in quality.

c. A sudden rate of flow increase has much greater effect than a gradual increase made over a period of 10 or 20 minutes.

d. The duration of high rate of flow has little effect on the total amount of material flushed from the bed.

e. Different types of solids filtered from water have varying degrees of sensitivity to the flushing action of a rate of flow increase. This indicates that the forces serving to retain the solids in the filter differ for different solids.

4. EVALUATION OF GRANULAR FILTERS FOR CONTACT WATER SOFTENING

(Wenck, Norman, M.S. thesis, Iowa State University Library, 1963.)

A recent development in water treatment has been the renewed interest in the use of the filter sand bed as a contact coagulation bed for the clarification of turbid surface waters. The large surface area of the sand grains seems to provide ideal conditions to encourage rapid and complete clarification by coagulation. Operators of lime softened water have noticed for years that an unstable water fed to a sand filter will deposit calcium carbonate in the filter.

This study was conducted first to determine if a contact softening process on a fixed granular bed would produce water of acceptable hardness and turbidity, and second to examine the factors which would determine its practicability. Such factors would include: permissible filtration rate, run length, media type and size, flow direction, and water stability.

A rapid sand pilot plant was used in this investigation. Caustic soda or slaked lime were used as softening chemicals. The pilot plant was operated with various media, at various rates, and in both upflow and downflow direction. Samples were withdrawn at incremental depths to study the progress of the softening reaction.

The following conclusions resulted:

a. Total hardness and calcium hardness removal are predominantly affected by the contact surface of the filter media.

b. Total hardness and calcium hardness removal are slightly reduced by higher filtration rates.

c. Coarse filter media gave much more acceptable run length than fine media.

d. Upflow filtration with a graded sand filter increased the run length about five times more than downflow filtration.

e. Less chemical was required to attain a desired degree of softening than would be predicted by stoichiometric calculations.

f. Magnesium hardness was precipitated in the filter, but an excessive amount was washed through into the filter effluent.

g. The contact softening process appears to be practical only for a water of moderate hardness (below 250 ppm as $CaCO_3$) with little or no magnesium. Such a water could be softened to 40 to 50 ppm total hardness.

h. Mechanical problems due to deposition in the pipes, valves and on the media were eliminated by proper operational procedures.

5. THE EFFECT OF BACKWASH TECHNIQUES ON EFFLUENT QUALITY FROM SAND FILTERS

(Johnson, Robert L. M.S. thesis. Iowa State University Library, 1963.)

The required back wash rates for sand filters have been guided since 1929, by the 50 percent sand expansion recommended by Hulbert and Herring. With the use of coarser sands, this expansion required very high rates of back wash, particularly when water is warm.

The effect of back wash rate and back wash duration on subsequent effluent quality has been investigated on a full-plant scale. The optimum rate for the coarse sand in use, 0.63 mm effective size, was found to be 16 gpm/sq ft. At this rate, the sand expansion was only 17 percent. Lower or higher rates of back wash resulted in poorer effluent quality. The optimum duration was between six and twelve minutes. A theoretical analysis of the forces acting on a sand grain during back-washing supports the experimental observations.

It was observed that the turbidity of the backwash water cannot be used as a sole criterion as to the cleanliness of the sand. It must be used in conjunction with observations of effluent quality and long term good physical condition of the sand bed.

This research does not support the results of the early experiments which recommended 50 percent sand expansion. Acceptance of lower expansion will mean savings in cost of back wash piping, equipment, and in filter underdrain systems.

PROFESSIONAL PROJECT PERSONNEL:

September 1, 1962 through April 30, 1964

	Name	Title	Period	% of Time on Project	Source of Support
1.	Paul E. Morgan	Associate Professor	Sept 62-April 64	10%	Univ funds
2.	E. Robert Baumann, PhD	Professor	Sept 62-April 64	25%	Univ funds
3.	John L. Cleasby, PhD	Associate Professor	Sept 62-May 63	22%	Grant Funds
			July 63-April 64	24%	Grant Funds
4.	C. S. Oulman, PhD	Assistant Professor	Sept 62-June 63	75%	Grant Funds
			July 63-Aug 63	37%	Grant Funds
			Sept 63-Dec 63	15%	Grant Funds
			Jan 64-April 64	17%	Grant Funds
5.	Bruce B. Hall	Research Graduate Assistant	Dec 62-Feb 64	50%	Grant Funds
6.	James F. Hawley	Res. Grad. Asst.	Dec 62-Feb 64	50%	Grant Funds
7.	Perialwar Regunathan	Res. Grad. Asst.	Dec 63-April 64	50%	Grant Funds
8.	Donald Burns*	Graduate Student	Sept 63-April 64	25%	USPHS Traineeship
9.	James H. Dillingham*	Graduate Student	Sept 62-Feb 63	25%	USPHS Traineeship
			March 63- April 64	-	PHS Fellowship
10.	Mustafa Abdulrahman*	Graduate Student	Sept 62-Feb 64	20%	Self Supported

FOREIGN TRAVEL: None

* These personnel were graduate students in sanitary engineering who elected to conduct their research in diatomite filtration of water. Their research expenses were supported by the grant. Burns and Dillingham are continuing PhD research in this area.

VITA

ADDITIONAL PROFESSIONAL PERSONNEL

Note: Biographical sketches for P. E. Morgan, E. R. Baumann, J. L. Cleasby, C. S. Oulman, J. H. Dillingham, B.B. Hall, and J. L. Hawley were included in the Application for Research Grant (WP-00196-04).

NEW PERSONNEL

Perialwar Regunathan

Born: Samugarengapuram, Madras State, India (February 23, 1940)
Graduated:
University of Madras, India, B.S. (Civil Engr.)* August, 1961
University of Madras, India, M.S. (San. Engr.)* May, 1962

Currently, a research graduate assistant supported by Grant Funds with one year of teaching experience in India.

*first class degrees.

Donald Edward Burns

Born: May 6, 1937 (Prairie City, Iowa)
Graduated:
Iowa State University, B.S. (Civil Engr.) May, 1963
Iowa State University, M.S. (Sanitary Engr.) (August, 1964)*

*Currently a U.S.P.H.S. Trainee working on his M.S. degree to be awarded in August, 1964. Has been awarded a DWSPC Research Fellowship to continue his studies to the doctorate. His doctoral research will extend his M.S. research studies into the area of "Removal of Particulate Matter on Coated Filter Media."

LIST OF PUBLICATIONS ON DIATOMITE AND SAND FILTRATION

DIATOMITE

Supported by PHS Research Grant WP-00196, Division of Water Supply and Pollution Control

1. Cleasby, John L. Turbidimetric control of filter effluent quality. Journal A.W.W.A., 52:11, p 1411-1415, November, 1960.
2. LaFrenz, R. L. and E. R. Baumann. Optimums in diatomite filtration. Journal A.W.W.A., 54:7, p 847-851, July, 1962.
3. Baumann, E. R., Cleasby, J. L. and R. L. LaFrenz. A theory of diatomite filtration. Journal A.W.W.A., 54:9, p 1109-1119, September, 1962.
4. Baumann, E.R. and R. L. LaFrenz. Optimum economical design for municipal diatomite filtration plants. Journal A.W.W.A., 55:1, p 48-58, January, 1963.
5. Baumann, E.R. and C.S. Oulman. Iowa State: Pilot studies of diatomite filtration.
   Water Works Engineering, 116:5, p 366-368, May, 1963.
6. Baumann, E. R. and C. S. Oulman. Modified form of Diatomite filtration equation. Journal, A.W.W.A., 56:3, p 330-333, March, 1964.
7. Oulman, C. S. and E. R. Baumann. A plastic microelectrophoresis cell for zeta potential measurements. Journal, Water Pollution Control (in press-Industry Idea Clinic, 1963 Annual Meeting).
8. Oulman, C. S. and E. R. Baumann. A photoelectric settlimeter for sedimentation studies. Journal, Water Pollution Control (in press-Industry Idea Clinic, 1963 Annual Meeting).
9. Oulman, C. S. and E. R. Baumann. Streaming potentials in diatomite filtration of water.
   Journal, A.W.W.A. (In press-accepted for publication following Annual Meeting in June, 1964).

10. Dillingham, James H. and E. R. Baumann. Hydraulic and particle size characteristics of some diatomite filter aids. Journal, A.W.W.A. (In press, accepted for publication March 17, 1964).

11. Baumann, E. R., Cleasby, J. L. and P. E. Morgan. Theoretical aspects of diatomite filtration. Water and Sewage Works, (in press, accepted on February 21, 1964 for publication in early summer 1964.)

Misc. Baumann, E. R. Pure water while you wait. The American City, p 23, December, 1963.

SAND

Supported by the Iowa Engineering Experiment Station

12. Cleasby, J. L. and E. R. Baumann. Selection of sand filtration rates. Journal A.W.W.A., 54:5, p 579-602, May, 1962.

Note: This paper was presented the PUBLICATIONS AWARD in 1962 by the American Water Works Association "for the most notable contribution to the science of public water supply development published by the Association".

13. Cleasby, J. L. and E. R. Baumann. Selection of optimum filtration rates for sand filters. Iowa Engineering Experiment Station, Bulletin 198, January 24, 1962.

14. Cleasby, J. L. Single-stage softening permits filtration at 4 GPM/Square foot. Water Works Engineering, 115:9, p 733, 767, 768, September, 1962.

15. Cleasby, J. L., Williamson, M. M., and E. R. Baumann. Effect of filtration rate changes on quality. Journal A.W.W.A., 55:7, p 869-880, July, 1963.

16. Johnson, R.L. and J. L. Cleasby. Effect of backwash techniques on filter effluent quality. Journal, Sanitary Engineering Division, A.S.C.E. (Submitted April, 1964).

17. Baumann, E. R., Willrich, T. L., and D. D. Ludwig. For a purer water supply consider ---- Prechlorination. Agricultural Engineering, 44:3, p 138, March, 1963. (Condensation of ASAE Paper No. 62-208)

LIST OF PAPERS PRESENTED OR TO BE PRESENTED ON FILTRATION

NINTH SUMMER INSTITUTE IN WATER POLLUTION CONTROL, MANHATTAN COLLEGE, NEW YORK

June 23, 1964 (9-12 a.m.)

1. Filtration - E. Robert Baumann
   (Lecture on theory of sand and diatomite filtration, factors affecting filter performance, design of filtration systems)

84TH AMERICAN WATER WORKS ASSOCIATION ANNUAL CONFERENCE, TORONTO, CANADA

June 3, 1964 (Purification Division)

2. A.W.W.A. Task Group Report on Diatomite Filtration - E. Robert Baumann

June 2, 1964 (Committee on Research)

3. Use of Streaming Potentials in Filtration Research
   C. S. Oulman and E. R. Baumann
   (Paper presented by Dr. Oulman)

4. Coatings for Filter Media
   C. S. Oulman, Donald Burns, E. R. Baumann
   (Paper presented by E. R. Baumann)

1964 CONVENTION - EXPOSITION OF THE NATIONAL SWIMMING POOL INSTITUTE, CHICAGO, ILLINOIS

January 11, 1964

5. Theoretical Aspects of Diatomite Filtration
   E. R. Baumann, J. L. Cleasby, and P. E. Morgan
   (Paper presented by E. R. Baumann)

36TH ANNUAL MEETING OF WATER POLLUTION CONTROL FEDERATION, SEATTLE WASHINGTON

October 9, 1963 (Industry Idea Clinic)

6. A plastic microelectrophoresis cell for zeta-potential measurements
   C. S. Oulman and E. R. Baumann
   (Paper presented by C. S. Oulman)

7. A photoelectric settlimeter for sedimentation studies
   C. S. Oulman and E. R. Baumann
   (Paper presented by E. R. Baumann)

18TH ANNUAL MEETING, IOWA SECTION, AMERICAN WATER WORKS ASSOCIATION,

SIOUX CITY, IOWA

October 17, 1964

8. The Role of Zeta Potential in Coagulation and Filtration
   C. S. Oulman

83RD AMERICAN WATER WORKS ASSOCIATION ANNUAL CONFERENCE, KANSAS CITY, MISSOURI
May 21, 1963
9. Diatomite Filtration - E. Robert Baumann

82ND AMERICAN WATER WORKS ASSOCIATION ANNUAL CONFERENCE, PHILADELPHIA, PENNSYLVANIA
June 19, 1962
10. Theory of filtration applicable to diatomite filters
E. R. Baumann and R. L. LaFrenz
(Paper presented by E. R. Baumann)

1962 CONFERENCE OF STATE SANITARY ENGINEERS, WASHINGTON, D.C.
May 22, 1962 (Water Supply Workshop)
11. Use of Diatomite Filters for Public Water Supplies
E. R. Baumann

JOHNS-MANVILLE WATER FILTRATION SEMINAR, MANVILLE, NEW JERSEY
December 12 and 13, 1961
12. University Research in Filter Aid Filtration
E. R. Baumann

INTERNATIONAL WATER CONFERENCE OF THE ENGINEERS SOCIETY OF WESTERN PENNSYLVANIA, PITTSBURG, PENNSYLVANIA
October 23, 24, 25, 1961
13. Formal Invited Discussion of Paper by G. R. Bell entitled "Coagulant Coatings Open New Applications to Filter Aids"
(Discussion by E. R. Baumann)

15TH ANNUAL MEETING, IOWA SECTION, AMERICAN WATER WORKS ASSOCIATION, DES MOINES, IOWA
October 21, 1960
14. Filtration Rate Research at Iowa State University
J. L. Cleasby

DEGREES AWARDED WHERE DIATOMITE FILTRATION RESEARCH EXPENSE WAS COMPLETELY OR PARTIALLY GRANT SUPPORTED

	Candidate	Degree	Date Awarded
1.	Robert L. LaFrenz	Ph.D.	June, 1961
2.	Charles S. Oulman	Ph.D.	February, 1963
3.	Mustafa S. Abdulrahman	Ph.D.	February, 1964
4.	James H. Dillingham	M.S.	June, 1963
5.	James F. Hawley	M.S.	February, 1964
6.	Bruce B. Hall	M.S.	February, 1964

DEGREES AWARDED WHERE RESEARCH WAS IN ASSOCIATED SAND FILTRATION AREA

1.	John L. Cleasby	Ph.D.	November, 1960
2.	Hugh Munson	M.S.	June, 1961
3.	Daniel D. Ludwig	Ph.D.	August, 1961
4.	Marvin M. Williamson	M.S.	June, 1962
5.	Robert L. Johnson	M.S.	August, 1963
6.	Norman Wenck	M.S.	June, 1963

THESES RESULTING FROM RESEARCH AT IOWA STATE UNIVERSITY IN DIATOMITE FILTRATION

Supported by Iowa Engineering Experiment Station

1. Philips, Eugene, Jr. Recommended practices for the design and operation of diatomite precoat filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1957.

Supported by PHS Research Grant RG-5958A (Small Grant Program)

(September 1, 1958-August 30, 1959)

2. Miley, James F. Operation of pressure vs. vacuum diatomite filters using iron-containing water. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1959.

Supported by Iowa Engineering Experiment Station

3. Wiggers, R. G. Iron removal from natural and synthetic waters using diatomite filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1960.

4. LaFrenz, R. L. Effect of chemical coagulation on permeability of diatomite water filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1960.

Supported by PHS Research Grant WP-00196, Division Water Supply and Pollution Control (October 1, 1960-date)

5. LaFrenz, R. L. Design of municipal diatomite filters for iron removal. Unpublished Ph.D. thesis, Iowa State Univesity Library, Ames, Iowa, 1961.

6. Oulman, C. S. Streaming Potentials in diatomite filtration of water. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1963.

7. Dillingham, James F. Hydraulic and particle size characteristics of some diatomite filter aids. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1963.

8. Hall, Bruce B. Permeability of various grades of diatomite filter cake containing flocculent iron oxide. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1964.

9. Hawley, James F. Permeability of diatomite filter cakes containing various flocculent solids. Unpublished Master of Science thesis, Iowa State Univesity Library, Ames, Iowa, 1964.

10. Abdulrahman, Mustafa S. Effect of ions in solution on the permeability of diatomite filter aids. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1964.

THESES RESULTING FROM RESEARCH AT IOWA STATE UNIVERSITY IN SAND FILTRATION

Supported by PHS Research Grant RG-6755A (Small Grant Program)

1. Cleasby, John L. Selection of optimum filtration rates for sand filters. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1960.

Supported by Iowa Engineering Experiment Station

2. Munson, Hugh. Iron removal vs. depth in a sand filter. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1961.

3. Williamson, Marcy. Effect of rate disturbances on the qualities of filtered water. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1962.

4. Wench, Norman. Evaluation of granular filters for contact water softening. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1963.

Supported by Iowa Engineering Experiment Station and City of Ames, Iowa

5. Johnson, Robert L. The effect of backwash techniques on effluent quality of sand filters. Unpublished Master of Science thesis, Iowa State University Library, Ames, Iowa, 1963.

Supported by Iowa Engineering Experiment Station

6. Ludwig, Daniel. Filtration and chlorination of small water supplies. Unpublished Ph.D. thesis, Iowa State University Library, Ames, Iowa, 1961.

PROGRESS REPORT IN FOUR PARTS

CO-PRINCIPAL INVESTIGATORS

Paul E. Morgan
E. R. Baumann

I THEORETICAL ASPECTS OF DIATOMITE FILTRATION

E. R. Baumann
John L. Cleasby
Paul E. Morgan

II MODIFIED FORM OF DIATOMITE FILTRATION EQUATION

E. R. Baumann
C. S. Oulman

III HYDRAULIC AND PARTICLE SIZE CHARACTERISTICS OF SOME DIATOMITE FILTER AIDS

James H. Dillingham
E. R. Baumann

IV STREAMING POTENTIALS IN DIATOMITE FILTRATION OF WATER

C. S. Oulman
E. R. Baumann

V COATINGS FOR FILTER MEDIA

C. S. Oulman
Donald E. Burns
E. R. Baumann

VI PERMEABILITY OF FILTER CAKES CONTAINING VARIOUS FLOCCULENT SOLIDS

J. L. Cleasby
E. R. Baumann

PART I

THEORETICAL ASPECTS OF DIATOMITE FILTRATION

E. Robert Baumann
John L. Cleasby
Paul E. Morgan

THEORETICAL ASPECTS OF DIATOMITE FILTRATION

by

E. Robert Baumann
Professor of Civil Engineering

John L. Cleasby
Associate Professor of Civil Engineering

Paul E. Morgan
Associate Professor of Civil Engineering

A Paper
For Presentation at The
1964 CONVENTION-EXPOSITION
National Swimming Pool Institute
Conrad Hilton Hotel
Chicago, Illinois

January 11, 1964

Iowa State University
Engineering Experiment Station
Ames, Iowa

THEORETICAL ASPECTS OF DIATOMITE FILTRATION

INTRODUCTION

Fpr the past 10 years, one of the main research activities of the Sanitary Engineering Section of the Department of Civil Engineering and the Engineering Experiment Station of Iowa State University has been the study of the process of filtration of water. All of the studies completed, in progress, or in the planning stage have been concerned with two basic questions:

1. How can a filter be designed, constructed, and operated to provide a better quality of filtered water?
2. How can a filter be designed, constructed, and operated to provide water of the desired quality at least cost?

Few filters are designed on an orderly scientific basis to provide water of the required quality at the least cost. Instead, a filter is designed on the basis of "past experience" to provide water of the desired quality at a cost which the consumer is willing to pay. Today, we are in the process of changing from the "art" of water filter design to the "science" of water filter design.

To design a filter scientifically to operate effectively with maximum economy, it is necessary to know:

1. How a given particle is removed on a filter,
2. What factors affect the design and operation of a filter, and
3. How these factors affect the economy of operation.

Although studies are being conducted at Iowa State University which can be applied in both sand filter and diatomite filter design, this paper is confined to a discussion of the principles involved in diatomite filtration. Although work has been directed primarily towards filtration of potable water for municipalities and industry, the principles to be discussed apply equally to the filtration of water in swimming pools[2,4,7].

COMPARISON OF FILTRATION COSTS

BASIS OF COST COMPARISON

An engineer can design many different diatomite filtration plants that will provide the desired quality of filtered water at a reasonable cost. The design of a plant involves three major factors affecting filter operations:

1. The filtration rate, Q, in $\frac{\text{gal}}{\text{min}\cdot\text{ft}^2}$
2. The pressure drop across the filter, H, in feet of water
3. The grade and concentration of body feed filter aid to be used

The objective of each designer of filters should be to choose the proper combination of filtration rate, terminal pressure drop, and body feed type and rate that will produce filtered water at the least cost consistent with the reliable production of a quality water. A method of designing such filters on a scientific basis has recently been proposed[4].

The comparison of the costs of several different filter designs should be made on the basis of their capitalized costs. The capitalized cost may be defined as the sum of money which would be required now to build, operate, and perpetutate forever the plant. Equation 1 shows the

Equation 1. Capitalized Cost Equation

$$CC = C + \frac{O}{r} + \frac{(C - S)}{(1 + r)^n - 1}$$

where: CC = Capitalized cost, \$, representing the sum needed today to build, operate, and perpetuate the filtration plant

C = Cost to construct the plant, \$

$C \sim$ rate of filtration, Q

O = Annual operating cost, \$

$O \sim$ total cost of power, labor, diatomite and maintenance

S = Salvage value of plant after period of "n" years

r = Interest paid on borrowed money, %

n = Useful life of plant, years

Annual Plant Cost = Annual Interest on Capitalized Cost

= (CC) · r

Equation 2. Operating Costs for Diatomite Filtration

Annual Operating Costs = Power Costs + Labor Costs + Diatomite Costs + Maintenance Costs

$$O = P + L + D + M$$

where: O = Annual operating costs, \$

P = Annual power costs, \$

$P \sim$ terminal head, H (Figure 2)

L = Annual labor costs, \$

$L \sim$ length of filter run, t (Figure 3)

D = Annual filter aid costs, \$

$D \sim$ concentration of body feed, C_D

M = Annual maintenance and repairs, \$

basic capitalized cost equation. Some of the money, C, would be expended immediately to build the plant. Another amount, $\frac{O}{r}$, would be invested at simple interest such that the annual interest on the invested capital would pay the average yearly operating expense of the plant. A third amount, $\frac{(C - S)}{(1 + r)^n - 1}$, would be set aside at compound interest. At the end of the useful life of the installation, this original invested sum and the interest earned would provide enough money to rebuild the original plant and yet keep the original sum available for reinvestment so that the plant could be perpetuated. Of the several alternative designs, the plant with the lowest *capitalized cost* should be the plant design adopted.

The yearly cost or annual expense of the plant is equal to the annual interest on the capitalized cost. If the annual interest on the capitalized cost is divided by the total yearly water production, the cost of producing a gallon of filtered water can be determined. In example 1, for example, the cost of filtering water would be 7.42¢/1000 gallons.

FIRST COST AND DEPRECIATION

To use the capitalized cost equation, the first cost of a plant must be determined. Once the engineer has decided on the various types of equipment required for filter operation, the type of building construction, and the plant location, the first cost of a plant is a function of the filter area to be provided. The filter area in turn will be a function of the required plant capacity and the rate of filtration used. The effect of filter area on filter cost can be plotted (figure 1) and the equation representing the relationship written. The relationship will vary depending on construction costs in the area where the plant is to be built.

Example 1:

What is the cost of filtering 1000 gallons of water in the following plant?

Population = 2000

Annual Plant Production = 73 mg/year

First Cost of Plant = \$28,000

Salvage Value of Plant (15 years) = \$15,000

Annual Operating Cost (power, labor, diatomite and maintenance) O = \$3650

Rate of Interest = 4% (0.04)

Life of Filter Equipment, n = 15 years

$$CC = \$28{,}000 + \frac{\$3650}{0.04} + \frac{(\$28{,}000 - \$15{,}000)}{(1.04)^{15} - 1}$$

$$= \$28{,}000 + \$91{,}250 + \frac{\$13{,}000}{1.8 - 1}$$

$$= \$28{,}000 + \$91{,}250 + \$16{,}250 = \$135{,}500$$

$$\text{Annual Cost} = (CC) \times r = \$135{,}500 \times 0.04 = \$5420$$

$$\text{Filtration Cost} = \frac{542{,}000¢}{73{,}000 \text{ thousand gallons}} = 7.42¢/1000 \text{ gal}$$

The first cost of a diatomite filter plant represents the cost of land, a building to house the plant, the filters, piping, pumps, filter aid feeding equipment, miscellaneous controls and gages, engineering, legal, and other miscellaneous expenses. Not all of the items will have the same useful life. The building may last for 30 to 50 years, the filters for 15 to 20 years, and the pumps and chemical feeders for only 10 to 12 years. For this reason, the depreciation item in the capitalized cost equation may include several (C - S) items to be perpetuated.

After the engineer has determined the relationship between first cost of the plant and filter area as shown in Figure 1 and has determined the probable life of the various units to be included in the diatomite filtration plant, the first and last terms in the capitalized cost equation can be calculated readily. The main items of filtration cost, however, will generally be involved in the annual operating cost.

ANNUAL OPERATING COSTS

The annual operating costs of the diatomite filter plant will include the cost of power, the cost of labor, the cost of diatomite, and the miscellaneous maintenance costs (equation 2).

A diatomite filter is usually so designed that the water is filtered against a fixed terminal pressure drop across the filter. Since the power costs are determined by the volume of water filtered and the total head pumped against, the annual cost of power expressed in cents per thousand gallons can be related directly to the terminal pressure drop across the filter cake which is incorporated in the filter design. If a filter is operated under similar flow conditions to a pressure drop of 50 ft of head instead of 25 ft of head, the power costs will be doubled. A typical relationship between power costs and terminal head is shown in figure 2.

In the operation of a diatomite filter plant, a diatomite filter is ordinarily backwashed and reprecoated manually at the termination of each filter run. If the filter run lasts only an hour, labor will be required continuously for this purpose. But if a filter run is extended over a period of at least one day, an operator will only be required for about one-half hour for the backwashing and precoating operation and will be required to check the operation of the filter at least once per day. In general, the cost of labor will decrease significantly with the length of filter run up to a filter run length of about 1 day. For filter runs longer than one day, the labor costs become relatively constant per day (figure 3).

The total filter aid costs will be determined by the amount of filter aid used for precoat and the amount of filter aid used in body feed. Since a constant body feed concentration will normally be used when a plant is designed to filter a water containing a fixed amount of suspended solids, a savings in filter aid can be effected only by filtering larger and larger quantities of water in each filter run. In this way, the amount of filter aid used as precoat can be used to produce more water per pound of diatomite used. The total amount of body feed which must be used will be a function of the concentration of suspended solids, C_{ss}, that will be present in the water to be filtered. As the concentration of solids increases, the concentrations of body feed required to maintain a porous filter cake will also increase. The determination of the proper concentration of body feed to be used is one of the most important items for the engineer to determine in filter design. This will require pilot plant work using the water which is to be filtered. Generally, the annual power costs and the annual labor costs can be predicted with a considerable degree of accuracy merely from a knowledge of local costs.

The annual maintenance and repair costs in a diatomite filter plant are difficult to predict. Maintenance and repair costs will increase with filter area and with the complexity of the diatomite filter installation. In general, it will be possible to approximate these costs with a satisfactory degree of accuracy.

LEAST COST APPROACH

Once the engineer has fixed the probable variation of first cost with variation in filter area, the power costs with variation in terminal pressure drop and the labor cost with variation in the length of the filter run, he can design a number of plants to determine the proper combination of filtration rate, $\underline{Q}$, terminal pressure drop, $\underline{H}$, and diatomite body feed concentration, C_D, which can be used and inserted in the capitalized cost equation to produce the least cost of filtration. Since there are an infinite number of combinations of these three factors an engineer might use in design, the task of making the calculations would be formidable if it were not for the availability of modern high-speed computers. To predict the effect of flow rate, terminal head loss, and body feed rate on the operation of a diatomite filter, an engineer will need to know the probable effects of each on filter operation.

FILTER OPERATION

EFFECT OF CONCENTRATION OF BODY FEED, C_D

One of the most important factors affecting the operation of a diatomite filter is the prudent use of body feed during a filter run[7,12].

Let us consider the case where an engineer conducts a series of pilot plant studies of filtration. In the pilot plant operation a diatomite filter is operated to filter the raw water at a constant rate of filtration to a constant terminal pressure drop but with varying amounts of body feed. The results of a typical series of curves will be shown in figure 4. In this figure the total volume of filtrate is plotted versus the total head loss across the filter in feet of water. The total head loss is the initial head loss through the clean precoat filter aid plus the head loss through the cake of body feed and suspended solids as it builds up as the volume of filtrate increases.

When no body feed is used and the water is filtered only through precoat filter aids, the head loss will increase logarithmically (and rapidly) as the volume of filtrate increases. This is because the suspended solids are removed on the surface of the filter aid and soon form an impermeable layer of solids which will not readily permit the passage of water. Once this impermeable layer is formed over the entire precoat surface, the head loss will rise very rapidly and further increase in the terminal pressure drop will not significantly increase the length of the filter run.

If we made a series of runs under exactly the same conditions but with different flow rates, we will obtain a series of curves as shown in Figure 5. Here, we find that we can filter larger volumes of water with higher flow rates before the terminal pressure drop is reached. Undoubtedly this is because the suspended solids are removed on the surface of the filter aid with the low filtration rates. However, as the filter rate is increased the suspended solids penetrate to a greater depth in the filter precoat and the time required for the formation of the impermeable surface layer is increased. The results in figure 5 demonstrate the effect of filtration rate on both the volume of filtrate and the length of the filter run[7]. Table 1 shows the effect of rate of filtration on the length of the run when the water is filtered through precoat diatomite without body feed. At a 1 gpm/sq ft filtration rate, the filter might produce 1000 gallons of filtrate and the length of run would be 1000 minutes. At a filtration rate of 5.3 gpm/sq ft, the volume of filtrate will increase to 2,430 gallons, but the length of run would be reduced to 459 minutes. Figure 6 demonstrates the fact that the volume of filtrate will increase with increasing filtration rate when water is filtered through a diatomite precoat without the use of body feed.

Figure 4 shows that if a very small amount of body feed is fed continuously during the filter run, the head loss may increase faster that it would when no body feed was used. This is true because the concentration is so small with very small amounts of body feed that there is not enough filter aid present in the filter cake to increase the cake porosity and all the body feed does is serve to increase the thickness of the impermeable layer. When this happens, the head loss will increase faster than if no body feed were used at all. Then the effect of filtration rate on the volume of filtrate and the length of run will be similar to that shown in table 1 and in figures 5 and 6.

When the body feed concentration is increased further to say 5 units as shown in figure 4, the body feed concentration will eventually reach a point where some increase in porosity is achieved in the filter cake. This will then serve to prevent the formation of an impermeable

Table 1. Effect of rate of filtration on the length of run when water is filtered through diatomite without body feed[7].

Rate of Filtration, $\frac{gal}{min \cdot ft^2}$	Volume of Filtrate, gals	Length of Run, minutes
5.3	2,430	459
4.0	2,200	550
3.0	1,900	633
2.0	1,530	765
1.0	1,000	1000

Table 2. Effect of rate of filtration on the volume of filtrate obtained per 100 feet of head loss and on the length of run when body feed is sufficient to provide a straight line relationship of head loss to volume of filtrate (Fig. 4).

Filtration Rate, $\frac{gal}{min \cdot ft^2}$	Q·t for 100 ft Head Loss, $\frac{gal}{ft^2}$	Run Length, minutes	Initial Head Loss, h_1, ft of Water
4	1,350	338	0.44
2	2,700	1,350	0.22
1	5,400	5,400	0.11
0.5	10,800	21,600	0.05

surface layer and the rate of build up of head loss with volume of filtrate will be delayed, but with an increase in cost for body feed filter aid. The relationship of head loss to volume of filtrate may still be concave upward but the body feed does serve to produce an increase in filtrate volume. When this amount of body feed is used, it is obvious that the volume of filtrate and the length of run can both be increased by making an increase in the terminal pressure drop across the filter. Similarly, the run length can be increased by reducing the rate of filtration.

If the concentration of body feed used is increased further, a point may be reached where the concentration of body feed is sufficient to provide the resulting filter cake with the characteristics of the filter aid rather than of the suspended solids which are removed. In this case, there will be a straight line rate of head loss build up with increase in the volume of filtrate. This is demonstrated in the curves for 10 and 20 units of filter aid as shown in figure 4. With further increases in the concentration of body feed, the slope of the straight line plot of head loss to volume of filtrate, we will get flatter and flatter. Eventually, however, with further increases in body feed so much body feed will be added unnecessarily that the slope of the relationship of head loss to volume of filtrate will again increase.

When the concentration of body feed is sufficient to produce a straight line relationship of head loss to volume of filtrate, the effect of flow rate on the head loss through the cake at any instant can be represented by a straight line as shown in figure 7. In this figure, it is obvious that if the flow rate is cut in half, the head loss through a given thickness of filter cake will also be cut in half. Therefore, if a filtration test is conducted with a concentration of body feed of say 10 units and a filter rate at 4 gpm/sq ft, a total of 1,350 gallons of filtrate might be obtained at a terminal head loss of 100 feet of water (figure 8). At the flow rate of 4 gpm/sq ft, a total filter run of 338 minutes will be obtained before the 100 ft terminal head loss is reached. If further runs are conducted at flow rates of 2, 1, and 0.5 gpm/sq ft, the other results as shown in figure 8 would be obtained. It is evident from figure 8 that a reduction in the rate of filtration will permit a significant increase in the volume of filtrate which is obtainable at the given 100 foot terminal head loss. For example, at the 2 gpm/sq ft filter rate, the filter would operate for 676 minutes to produce the 1,350 gallons of filtrate which were obtained with the 100 ft terminal head loss at the 4 gpm rate. After 676 minutes, filtration at 2 gpm/sq ft will produce the same thickness of filter cake as was obtained at the end of the 4 gpm/sq ft filter run. However, with a flow rate of 2 gpm/sq ft, the head loss through that cake is only one-half of the head loss which would be obtained with a 4 gpm/sq ft filter rate (figure 7). Therefore, after filtering 676 minutes (1,350 gallons of filtrate), the head loss would only be 50 feet of water. To provide 100 feet of head loss, another 1,350 gallons of filtrate/sq ft would have to be filtered and this would require another 676 minutes of filtration. Thus, at a 2 gpm/sq ft filter rate, the volume of filtrate for a 100 ft head loss would be doubled, and the run length would be increased by a factor of four times.

Similarly, if a 1 gpm/sq ft flow rate were used, this filter would operate for 1,350 minutes before it would produce the same volume of filtrate and the same thickness of cake that were produced at the end of the 4 gpm/sq ft filter run. Again, figure 7 indicates that the head loss through this thickness of cake would only be 1/4 of the head loss obtained at the 4 gpm/sq ft flow rate. Therefore, the head loss would only be 25 feet of water. To give a 100 foot head loss through this filter cake at a flow rate of 1 gpm/sq ft, the filter cake would have to be four times as thick to provide this thickness of filter cake, a total of 5,400 gallons of filtrate per sq ft would have to be filtered, and this would require 5,400 minutes of filter run.

With the 10 or 20 unit concentrations of body feed (figure 4) the effect of flow rate on the volume of water filtered per foot of head loss is shown in figure 9. The volume of filtrate produced decreases as the flow rate increases. In fact, the ratio of the volume of water filtered at the lower filtration rate to the volume of water filtered at the higher filtration rate, $\frac{Q_1 \cdot t_1}{Q_2 \cdot t_2}$, will vary directly with the ratio of the higher flow rate to the lower flow rate, $\frac{Q_2}{Q_1}$. In other words:

$$\frac{Q_1 \cdot t_1}{Q_2 \cdot t_2} = \frac{Q_2}{Q_1}$$

This result is directly opposite the results obtained when water was filtered through precoat only (figure 6).

Figure 10 shows a plot of the effect of flow rate on the length of run which would be obtained when either 10 or 20 units of body feed were used. Here the length of run per foot of head loss increased with a reduction in filter rate. In fact, the ratio of the length of run at the lower filtration rate, to the length of run at the higher filtration rate, $\frac{t_1}{t_2}$, will vary directly with the square of the ratio of the higher flow rate to the lower flow rate, $\frac{Q_2}{Q_1}$. For example:

$$\frac{Q_1 \cdot t_1}{Q_2 \cdot t_2} = \frac{Q_2}{Q_1}, \text{ and}$$

$$\frac{t_1}{t_2} = \frac{Q_2 \cdot Q_2}{Q_1 \cdot Q_1} = \left(\frac{Q_2}{Q_1}\right)^2$$

In summary the effect of the concentration of body feed used is as follows:

1. If no body feed is used, larger volumes of filtrate will be produced with an increase in the flow rate.
2. a. With the proper amount of body feed, the length of a filter run may be doubled by doubling the terminal head loss across the filter at the end of a filter run.

   b. The volume of filtrate per run may be doubled by cutting the flow rate in half. This will serve to increase the length of the filter run by a factor of 4 times and will increase the economy of filter aid use, since the same weight of precoat filter aid will be used to produce twice as much volume of filtrate.

FILTRATION THEORY

With the knowledge of the effect of body feed on filter operation, the engineer can determine the least cost of filtration. If he uses the proper amount of body feed, he can lower the labor costs to a minimum level by either increasing the terminal head loss or by reducing the rate of filtration. If he increases the terminal head loss, he will increase the power costs. If he reduces the filtration rate, he will reduce the filter aid costs but will increase the first cost of the plant because more filter area will be required. Thus, there must be an optimum combination of filtration rate, terminal pressure drop, and body feed concentration which will produce the lowest cost of filtration. The job of the designing engineer is to find this proper combination. To do this, the engineer will first have to complete a number of pilot plant studies to determine the effect of filtration rate and body feed concentration on filter operation, as shown in figures 4 and 8, with the concentrations of suspended solids that are present in the water to be filtered.

A theory of diatomite filtration has recently been proposed which reduces the number of pilot plant tests which must be made to predict the operation of a filter[5,6]. The total head loss in a filter, $\underline{H}$, is equal to the head loss in a precoat layer, h_1, plus the head loss in the body feed layer, h_2, (equation 3). The head loss in the precoat layer is a function of the rate of flow, the weight of filter aid used to precoat the filter septum, and an impermeability coefficient, K_3, which is characteristic of the precoat filter aid used. The head loss in the body feed layer is a function of the concentration of body feed used, the square of the filtration rate, the time of filtration, and an impermeability coefficient (K_4) which is characteristic of the body feed plus the suspended solids layer. A recently published paper develops the method which can be used to determine both the K_3 characteristic of the precoat filter aid and the K_4 characteristic of the body feed plus the suspended solids layer[6].

The method of determining the K_3 characteristic of filter aid is demonstrated in figure 11. Here a plot is made of the head loss, h_1, Equation 3. Diatomite Filtration Equation (water temperature constant)

Total head loss = head loss in precoat layer + head loss in body feed layer

$$H \quad = \quad h_1 \quad + \quad h_2$$

$$H = K_3QW_1 + K_4C_DQ^2t \times \frac{8.33}{10^6}$$

H = total head loss across filter cake, ft of water

Q = rate of filtration, $\frac{\text{gal}}{\text{min. ft}^2}$

W_1 = weight of precoat, $\frac{\text{lb}}{\text{ft}^2}$

K_3 = permeability characteristic of the precoat filter aid layer, $\frac{\text{min}\cdot\text{ft}^5}{\text{lb}\cdot\text{gal}}$

C_D = concentration of diatomite in body feed, ppm

t = length of filter run, min.

K_4 = permeability characteristic of the body feed plus suspended solids layer, $\frac{\text{min}\cdot\text{ft}^5}{\text{lb}\cdot\text{gal}}$

across a given weight of precoat filter aid vs QW_1. The slope of the straight line resulting represents a measure of the impermeability characteristic, K_3. Data are obtained for this plot by determining the head loss across a given weight of precoat filter aid per sq ft using different filtration rates or determining the head loss through a series of increasing weights of precoat with a constant filtration rate. In either case, a plot such as is shown in figure 11 will provide a measure of the K_3 characteristic of the filter aid.

A knowledge of the permeability characteristic, K_3, of a diatomite filter aid can be used to calculate the initial head loss across a filter as shown in equation 3. In addition, the K_3 characteristic may be used in determining a purchase specification for filter aid which will be used in filter operations. Studies have been conducted at Iowa State University to evaluate the typical K_3 value for various commercial grades of diatomite filter aid (table 3)[3,9]. In addition to determining the K_3 specification of filter aid, studies have been made to determine the average particle size of different commercial grades of filter aid. Studies have just been completed to determine answers to the following questions:

1. Is there a relationship between the K_3 of a filter aid, its ability to remove a flocculent suspended solid during filtration, and the hydraulic characteristics of the filter cake[10]?
2. Is there a relationship between the permeability coefficient characteristics K_3 of a filter aid and the K_4 resulting from its use in body feed to aid in building a porous filter cake[10]?

Table 3. Typical values of K_3 for various commercial grades of filter aid[3].

	Mean Particle Size, microns	Approximate K_3, $\frac{\text{min}\cdot\text{ft}^5}{\text{lb gal}}$
Johns-Manville Products		
Celite 560	50	0.24
Celite 545	21.0	0.73
Celite 535	16.2	1.00
Celite 503	12.8	2.08
Hyflo Super-Cel	9.5	3.57
Great Lakes Carbon Products		
Dicalite 5000	21.8	0.68
Dicalite 4200	19.3	0.84
Speedex	13.0	2.55
Speedplus	10.4	3.83
Eagle-Picher Products		
FW-60	32.0	0.46
FW-50	19.3	0.97
FW-20	17.0	1.39
FW-14	12.0	2.96

In the tests to evaluate the filtering and hydraulic characteristics of filter aids, several significant observations have been made and techniques developed:

1. A method has been developed for measuring the streaming potential (in millivolts) developed across a filter during filtration[13,14]. The streaming potential measurements have then been used to calculate the surface charge on diatomite filter aids. Commercial filter aid grades are found to have true negative surface charges in the range of 30 to 50 millivolts.
2. The streaming potential apparatus has been used for evaluating changes that can be made to both the filtering and hydraulic characteristics of filter aids by coating them with electropositive materials to change their surface charge from negative to positive[8,13,14]. These tests indicate that some iron salts and cationic polyelectrolytes can be used to coat the coarser filter aids to give them the filtering characteristics of finer grades of filter aids while retaining nearly their original hydraulic characteristics.
3. Recent studies have indicated that the filtering characteristics of a water are a function not only of the suspended solids of the water, but also of the dissolved cations and anions present[1]. K_3 studies with different waters have indicated that this permeability characteristic can vary plus or minus 20 percent due to presence of certain cations in solution. The ions appear to determine the thickness of the fixed layer of water around the filter aid and suspended

particles, and thus affect the characteristics of the pore space available for water flow.

To use equation 3 in the design of a diatomite filter to operate with least cost, we need to know values not only of K_3 but also of the permeability characteristic, K_4, of the body feed-suspended solids filter cake. Equation 3 can be used then to determine the relationship of head loss to the volume of filtrate for different flow rates, terminal head losses, and body feed rates. If a test filter run is conducted with a constant ratio of suspended solids to body feed at a constant flow rate, a relationship such as is shown in figure 12 may be obtained. If values of total head loss versus Qt, the volume of filtrate, are plotted, the slope of the straight line which results will be equal to $K_4 \cdot C_D \cdot Q$. Since the concentration of body feed used and the rate of filtration are known, the impermeability characteristics, K_4, of the filter cake used in that filter run can be calculated. From a second run using a different concentration of suspended solid to body feed will be obtained a new value of the impermeability characteristic, K_4, of the new filter cake. In a large number of runs conducted at Iowa State University, it has been found that a plot of K_4 versus the ratio of the concentration of suspended solids to the concentration of diatomite, C_{ss}/C_D, will plot as a straight line on log-log paper[6,10,11]. Typical results obtained with various types of iron-bearing waters are shown in figures 13 and 14.

To determine the effect of various factors on the relation of K_4 to the concentration of the suspended solids to concentration of diatomite ratio, tests have been made in which the iron removed by filtration is prepared from different chemicals[11]. Figure 14, for example, indicates that the K_4 which results from the filtration of iron-bearing waters prepared from ferric iron salts will give much higher values of K_4 than will the filtration of iron-bearing waters which are prepared from ferrous iron salts. This appears to indicate that the filtering characteristics of a filter cake are a function of the ion contents of the waters filtered as well as the characteristics of the solids themselves[1].

Figure 13 shows the variation in K_4 with the ratio of the concentration of solids to the concentration of diatomite for three filter cakes in which three different grades of diatomite filter aid were used. In all cases, the three grades of filter aid produced the same quality of filtered water. However, because the coarsest filter aid produced the lowest K_4 for a given weight of body feed, the coarsest filter aid will produce the least cost for filtration of the water if the filter aid cost per pound is the same.

Example 2 shows how the diatomite filter equation 3 can be used to predict the head loss which would be expected after filtering an iron-bearing water containing 4 ppm of iron with flow rates of 1, 2, and 4 gpm/sq ft. The results (example 2) with Celite 535 filter aid which has a K_3 characteristic of 0.74 show the head loss which would be obtained after a filter run of 1,440 minutes. Figure 8 shows a plot of the head losses versus volumes of filtrate which are obtained from the computations shown in example 2.

For an engineer to design the most economical filter plant, he will require a plot similar to figures 13 and 14 in which different grades of filter aid and different concentrations of filter aid are used to determine the relationship of K_4 to the ratio of the concentration of suspended

Example 2:

What is the head loss to be expected after filtering an iron-bearing water containing 4 ppm of iron under the following conditions?

Given: $Q = 1, 2, 4 \frac{gal}{min \cdot ft^2}$ Filter Aid: Celite 535 ($K_3 = 0.74$)

$W_1 = 0.15 \frac{lb}{ft^2}$ $t = 1440$ minutes

$C_D = 100$ ppm

Find: $\frac{C_{Fe}}{C_D} = \frac{4}{100} = 0.04 \quad \therefore K_4 = 22$ (Figure 13)

$$H = K_3QW_1 + K_4C_DQ^2t \cdot \frac{8.33}{10^6}$$

Q = 1 $H = (0.74 \times 1 \times 0.15) + \frac{(22 \times 100 \times 1^2 \times 1440 \times 8.33)}{10^6}$

$= 0.11 + 26.35 = \underline{26.46}$ ft of water @ t = 1440 min or 1440 gallons

Q = 2 $H = (0.74 \times 2 \times 0.15) + \frac{(22 \times 100 \times 2^2 \times 1440 \times 8.33)}{10^6}$

$= 0.22 + 105.4 = \underline{105.6}$ ft of water @ t = 1440 min or 2880 gallons

Q = 4 $H = (0.74 \times 4 \times 0.15) + \frac{(22 \times 100 \times 4^2 \times 1440 \times 8.33)}{10^6}$

$= 0.44 + 421.6 = \underline{422}$ ft of water @ t = 1440 min or 5760 gallons solids to be removed by filtration to the concentration of diatomite body feed. Regrettably, data of the type shown in figures 13 and 14 are not yet available for a variety of suspended solids. Tests are now planned at Iowa State University for determining such plots for the removal of the following types of suspended solids from water:

1. Laboratory waters containing Kentucky ball clay. Kentucky ball clay is the present standard turbidity used by the National Science Foundation in evaluating the effectiveness of a diatomite filter.
2. Laboratory waters containing kaolin.
3. Laboratory waters containing montmorillonite.
4. Natural surface waters containing natural turbidities.
5. Ground waters containing lime softening solids.

The first three studies are being conducted in the laboratories at Iowa State University where the suspended solids are added artificially to tap water. The tests with natural waters containing natural turbidities will be made in the Spring throughout the State of Iowa. In these studies, a U.S. Army standard truck-mounted military water treatment unit will be used in collecting field data.

COMPUTER APPLICATIONS

Using the capitalized cost equation, equation 1, the filtration equation, equation 3, and figures 13 and 14 for predicting the value of K_4 with different concentrations and grades of diatomite, the engineer can make calculations sufficient to produce the results shown in figure 15. Figure 15 shows the effect of head loss on the cost of filtration when water is filtered with a constant concentration of body feed and at a constant flow rate. A curve such as figure 15 might be prepared for each of several runs made with different concentrations of diatomite body feed and with a number of filtration rates. Thus, if 10 filtration rates are evaluated we would end up with ten curves similar to figure 15.

Ten body feed concentrations used at each flow rate would give 100 curves similar to figure 15. Since this would require far too much calculation and plotting time, a computer could be programmed to provide the final answer: the combination of flow rate, head loss, and body feed concentration that would provide least cost of filtration[6].

In figure 15, line D shows the first cost and depreciation cost of the filter plant in terms of the cost of producing 1000 gallons of water. Since the filtration rate is constant, the first cost will be constant regardless of whatterminal head loss is used across the filter. On the other hand, curve B shows the cost of power. As the head loss across the filter increases, the power consumption will also increase. Curve A shows the cost of labor. Since the length of the filter run will increase with the increase in terminal head loss, the labor costs will be reduced. Curve C shows the reduction of the cost in diatomite with increase in terminal head loss. If a higher head loss is used, more filtrate will be produced per given weight of precoat filter aid, and the total cost of filter aid will decrease with increase in terminal head loss. The total cost of filtration for this concentration of body feed and this filtration rate will be the sum of the individual costs of A, B, C, and D, represented by curve E. Thus, with this given concentration of body feed and with this given filtration rate, the filter should be operated at a terminal head loss of 100 feet of water and will produce water at a cost slightly under 6¢ per 1000 gallons. Unfortunately, however, this cost is only the least cost for this concentration of body feed and this filtration rate. Similar curves would have to constructed using other filtration rates to determine whether another filtration rate will produce a lower cost of filtering perhaps with a different terminal head loss across the filter.

Figure 16 shows the effect of the concentration of body feed on the total cost of filtration. The curves in figure 16 represent the typical total cost of filtration curve obtained with the same flow rate, but with other concentrations of body feed. By making the whole series of studies and plotting all of these curves, the engineer can arrive fairly rapidly at the design which would produce water at least cost. To do this effectively, however, it will be necessary to develop the mathematical expression for the total cost of filtering water in which the cost is expressed in terms of the three variables: (1) flow rate, (2) terminal pressure drop, and (3) body feed concentration. The mathematical expression for total cost will then have to be programmed for solution on a high-speed computer. These studies are now being undertaken and should be available to the engineering profession in the near future.

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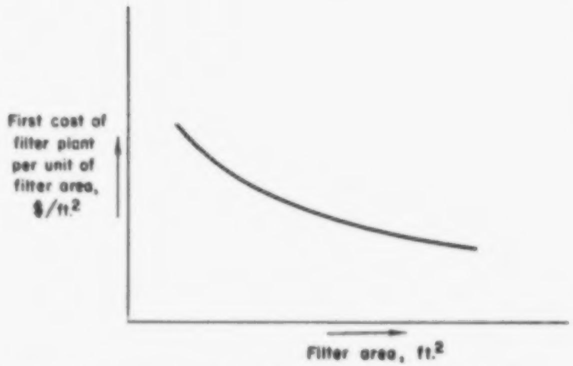


Fig. 1. First cost of a plant in terms of filter area

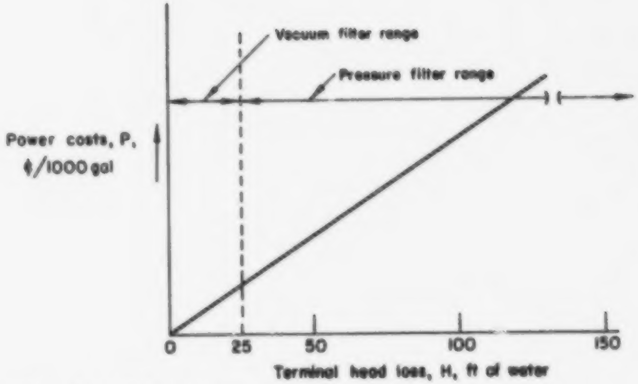


Fig. 2. Effect of terminal head loss on power costs

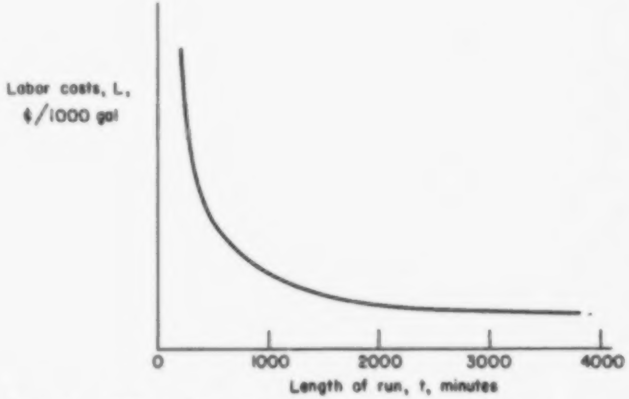


Fig. 3. Effect of length of filter run on labor costs

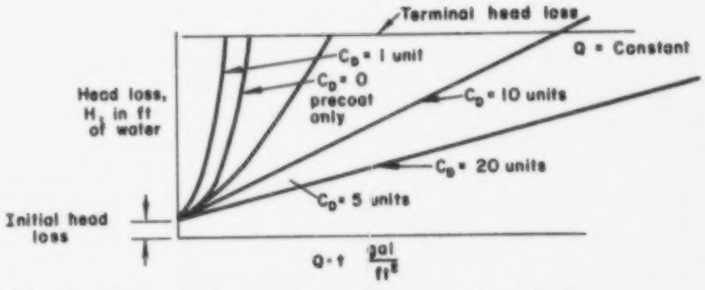


Fig. 4. Effect of varying the concentration of body feed, C_D, on the relationship of head loss to volume of filtrate

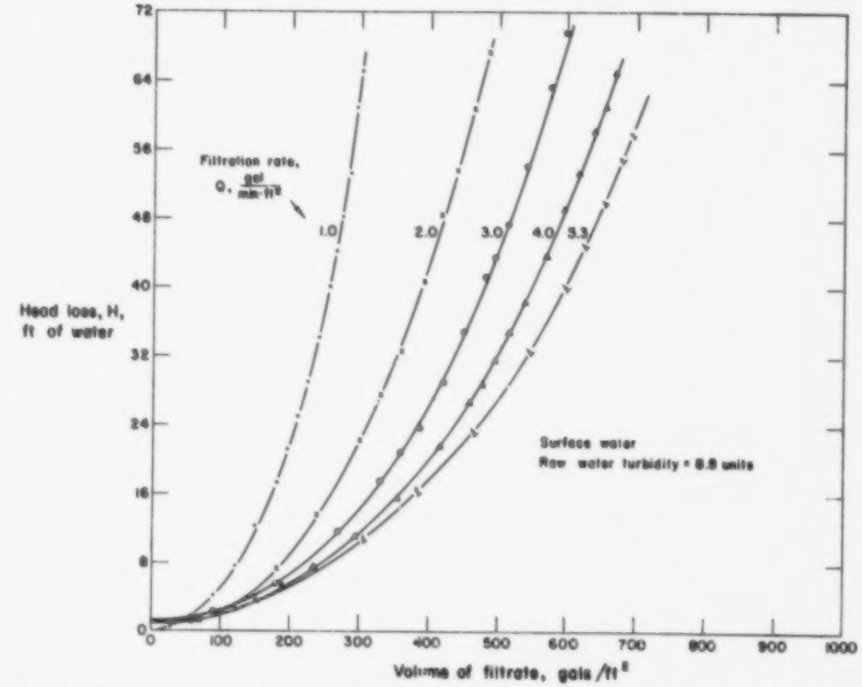


Fig. 5. Effect of rate of filtration on the relationship of head loss to volume of filtrate when filtering through a diatomite precoat without body feed

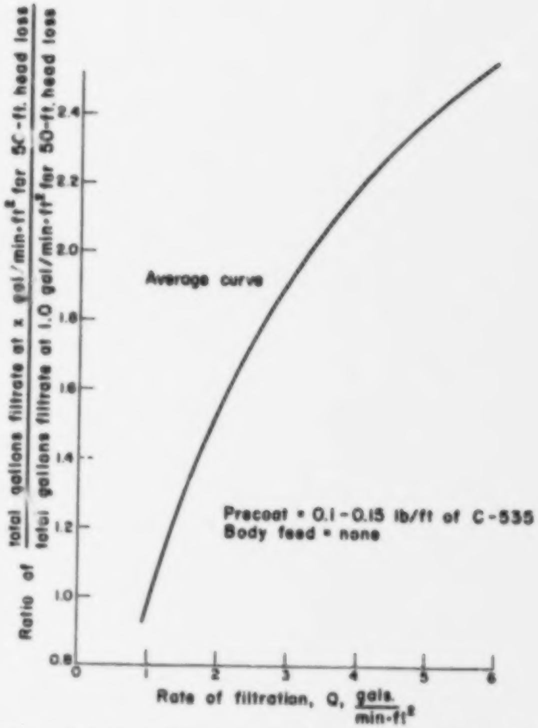
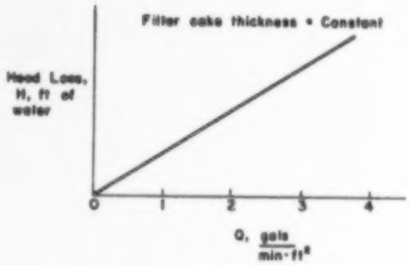


Fig. 6. Effect of rate of filtration on volume of water filtered per unit of head loss when filtering through a diatomite precoat without body feed



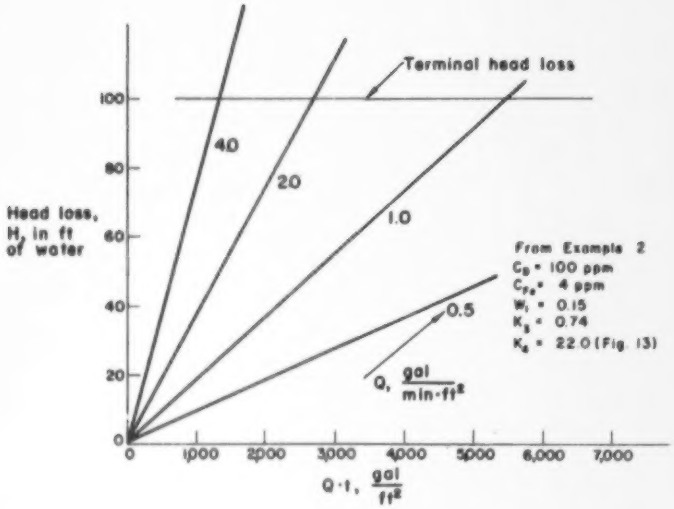


Fig. 7, left. Effect of rate of filtration on the head loss through a filter cake of constant thickness. Filter cake may be all diatomite or diatomite plus removed suspended solids such that the resultant cake provides a straight line relationship of head loss to volume of filtrate.

Fig. 8, right. Effect of rate of filtration on the relationship of head loss to volume of filtrate when body feed is sufficient to provide a straight line relationship of head loss to volume of filtrate (Fig. 4).

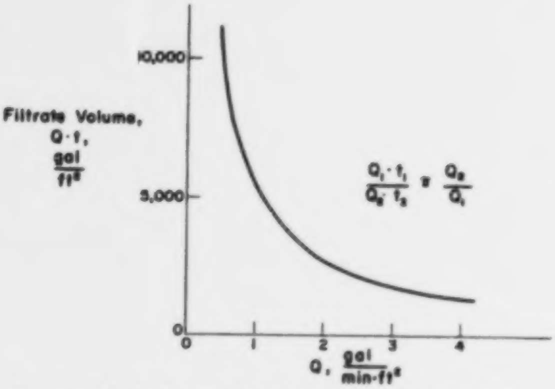


Fig. 9. Effect of rate of filtration on the volume of filtrate produced with a 100 ft terminal head loss when body feed is sufficient to provide a straight line relationship of head loss to volume of filtrate (Fig. 4)

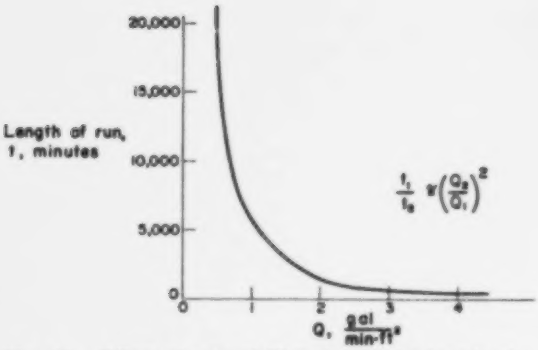


Fig. 10. Effect of rate of filtration on the length of filter run when body feed is sufficient to provide a straight line relationship of head loss to volume of filtrate (Fig. 4)

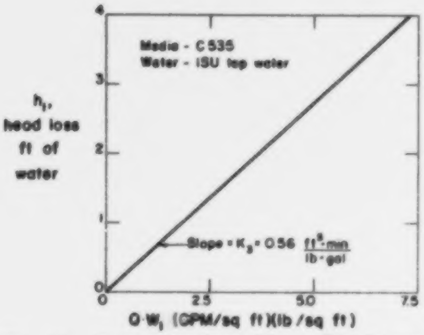


Fig. 11. Determination of K_3. Plot h_1 vs Q. W_1 and slope of line is K_3

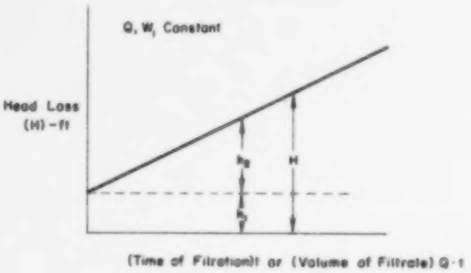


Fig. 12. Determination of K_4. Plot H vs Q·t in a typical filter run. Since h_2 equals $\frac{8.33}{10^6} K_4 C_D Q \cdot Qt$, the slope of the line equals $\frac{8.33}{10^6} K_4 C_D Q$. Since C_D and Q are usually known, K_4 can be calculated.

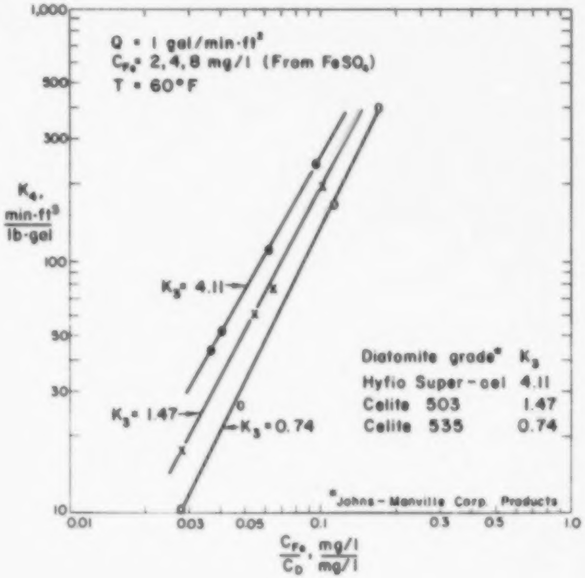
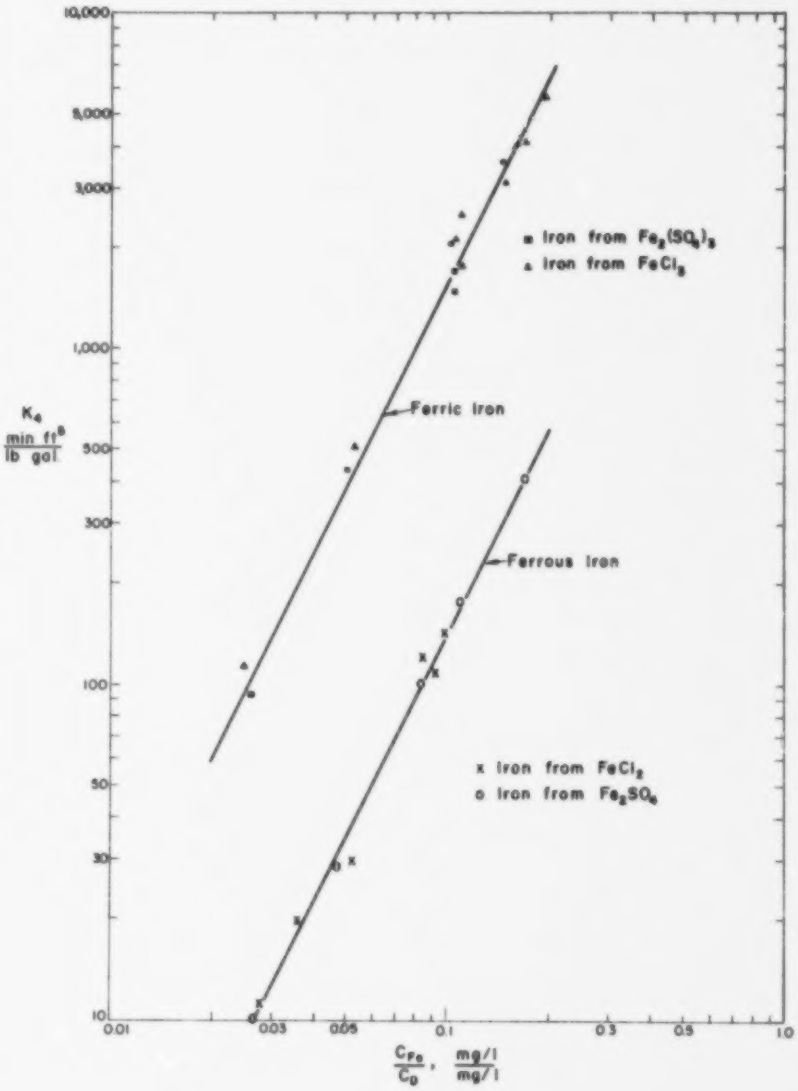


Fig. 13, above. Effect of grade of diatomite and K_3 on the relationship of K_4 to C_{Fe}/C_D

Fig. 14, right. Effect of source and type of iron on the relationship of K_4 to C_{Fe}/C_D



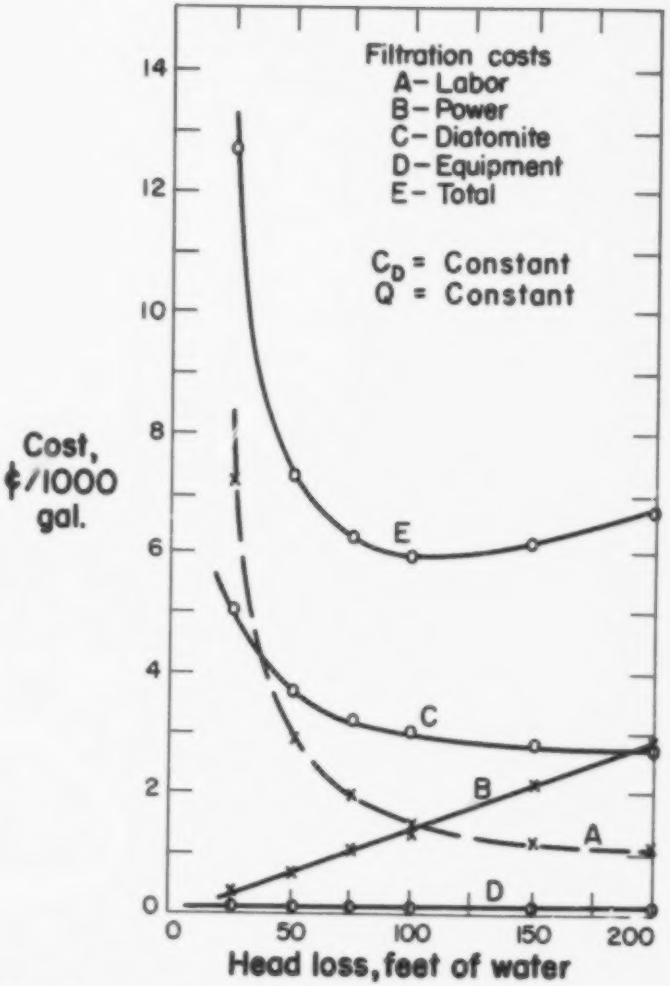


Fig. 15. Effect of head loss on filtration costs

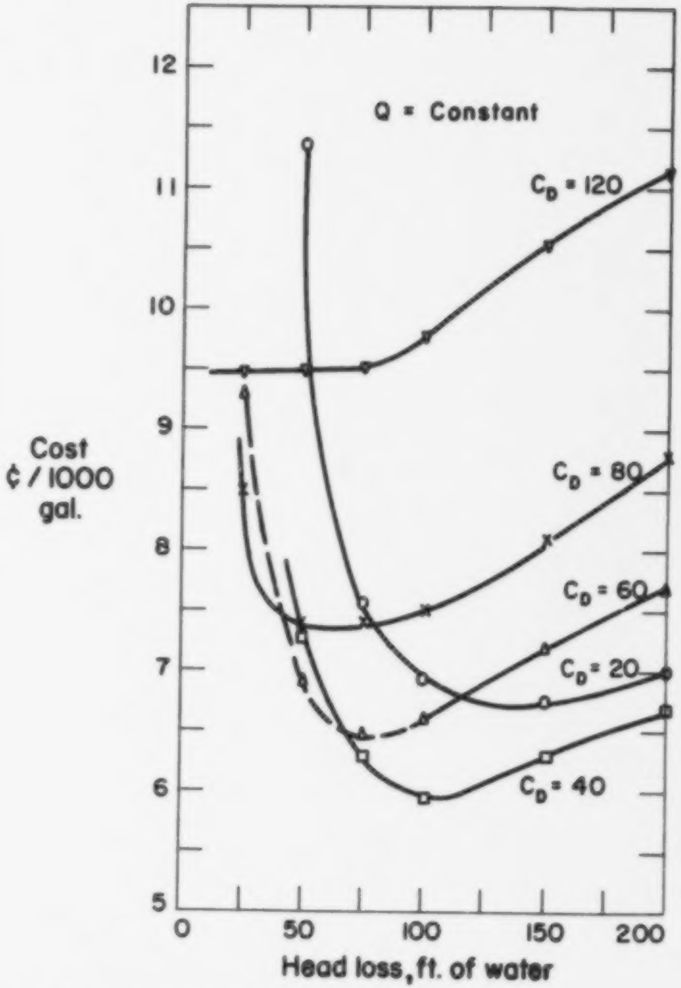


Fig. 16. Effect of body feed on filtration costs

PART II

MODIFIED FORM OF DIATOMITE FILTRATION EQUATION

E. R. Baumann
C. S. Oulman

Progress Report

MODIFIED FORM OF DIATOMITE FILTRATION EQUATION

by

E. Robert Baumann, Professor of Civil Engineering
Charles S. Oulman, Instructor of Civil Engineering

Project 388-S

of the

Iowa Engineering Experiment Station
Iowa State University
Ames, Iowa

April 1, 1963

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of Science and Technology / **Ames, Iowa**

ABSTRACT

An equation for constant rate diatomite filtration was recently published which contained two terms, K_3 and K_4, related to the permeability of the filter cake. These terms are shown in this paper to be variables which are functions of the absolute viscosity, μ, and bulk density, d, of the water being filtered, the gravitational constant, g, and the average specific resistances, α_1 and α_2, of the precoat and body feed portions of the filter cake. Average specific resistances, unlike either K_3 or K_4, are actually constants for given filter media. A modified form of the original filtration equation is proposed in which α_1 and α_2, μ, d and g are used instead of K_3 and K_4.

Modified Form of Diatomite Filtration Equation

Many filtration equations have been written since 1856 when Darcy checked Poiseuille's equation and found that it was valid for flow through sand and various other porous media[1]. According to Ruth most of these equations have degenerated into statements that filter flow rate is directly proportional to the driving force and inversely proportional to the filter cake resistance[2]. As such, Ruth states "all traces of Poiseuille's law are gone, and such a relation as Ohm's law might fully as well have been used."

Baumann et al, recently presented a filtration equation for constant rate diatomite filtration which suffers from the same simplification which Ruth wrote about, ie.:[3]

$$H = K_3QW_1 + K_4C_DQ^2t_x \frac{8.33}{10^6} \ldots\ldots\ldots (1)$$

where:

H = the total filter cake head loss in ft of water at 68°F.

K_3 = a constant which depends on the grade of diatomite and the water to be filtered,

K_4 = a constant which is a function of the filtering characteristics of the suspended solid to be removed and which is related to the ratio of suspended solids-to-body feed diatomite in the filter cake,

Q = the filtration rate in gpm/s ft,

W_1 = the weight of diatomite in the precoat layer in lb/sq ft,

C_D = the concentration of body feed used during filtration in ppm,

t = the time of filtration or length of run, in min.

Ruth's constant rate filtration equation derived from Poiseuille's work states that:

$$P - P_1 = \frac{dV}{d\theta}\frac{Z}{A^2}\frac{VP\,s\alpha}{(1 - ms)} \ldots\ldots\ldots\ldots (2)$$

where:

$P - P_1$ = the pressure drop through a homogeneous filter cake (equal to Hd, the head loss in ft of water times the bulk density of water in lb/cu ft) in lb/sq ft,

$dV/d\theta$ = the rate of filtration in cfs,

Z = the absolute viscosity of the filtrate usually represented by μ in lb sec/sq ft,

A = the filtering area in sq ft,

p = the density of the filtrate (equal to d/g, the bulk density in lb per cu ft divided by the gravitational constant in ft/sec^2) in lb sec^2/ft^4

s = the weight fraction of solids in the prefilt water*, lb/lb,

m = the ratio of wet to dry weight of the filter cake, lb/lb,

α = the average specific resistance of the portion of the filter cake through which a pressure drop exists in ft^2/lb sec^2.

The expression ms in Ruth's equation is the ratio of the weight of wet filter cake produced to the weight of the filter influent from which it was derived. Therefore, $(1 - ms)$ is the ratio of the weight of the filtrate to the weight of the influent. Hence, $s/(1 - ms)$ is the ratio of the weight of solids in the filter cake (either precoat or body feed and suspended solids) to the weight of filtrate produced in forming that cake.

In Ruth's equation, $\frac{VPs}{A(1 - ms)}$ is equal to W/g where W is the weight of diatomite per sq ft in the filter cake and g is the gravitational constant. If equation (2) is rewritten using the terms of the diatomite filtration equation, and if viscosity is represented by μ in centipoises:

$$H = \frac{(2.10 \times 10^{-5})}{(60)\ (7.48)^2}\frac{\mu\alpha}{gd}QW = 6.26 \times 10^{-9}\frac{\mu\alpha}{gd}QW \ldots (3)$$

where:

2.10×10^{-5} = the conversion factor to change Z in $\frac{\text{lb sec}}{\text{sq ft}}$, to μ in centipoises,

$(60)\ (7.48)$ = the conversion factor to change $\frac{dV}{d\theta}A$ in CFS/sq ft to Q in gpm/sq ft,

7.48 = the conversion factor to change d in lb/cu ft to d in lb/gal.

For the precoat:

$$H_1 = 6.26 \times 10^{-9}\frac{\mu\alpha_1}{gd}QW_1 \ldots\ldots\ldots (4)$$

and

$$K_3 = 6.26 \times 10^{-9}\frac{\mu\alpha_1}{gd} \ldots\ldots\ldots (5)$$

Using this relationship, it may be seen that K_3 is not really a constant but varies widely with temperature as the viscosity and density of the liquid being filtered change. Table 1 shows how the value of K_3 will vary with water temperature. Thus K_3 is not a true constant since it is temperature dependent. However, the specific resistance of the precoat layer, α_1 is a true constant.

A previous paper[3] indicated that filter aid "A" had a value of K_3 of 0.56 at a temperature of 68°F. Accordingly, the specific resistance of filter aid "A" would be:

$$\alpha_1 = \frac{K_3\,gd}{6.26 \times 10^{-9}\mu} = \frac{0.56 \times 32.2 \times 8.330}{6.26 \times 10^{-9}\mu}$$

$$\alpha_1 = 2.41 \times 10^{10} \text{ sq ft/lb sec}^2$$

---

* Prefilt water refers to the water entering the filter.

Table 1

Value of $\underline{K}_3$ for Diatomite Filter Aid "A" as a Function of Temperature[3].

Temperature, °F	Absolute Viscosity[4] μ, of water, Centipoises	Bulk Density of Water[4], d, lb/gal	K_3 $\overline{(\text{min})(\text{ft}^3)/(\text{lb})(\text{gal})}$
40	1.5433	8.345	0.86
60	1.1241	8.337	0.62
68	1.0050	8.330	0.56
80	0.8609	8.317	0.48
100	0.6843	8.287	0.38

For the part of the cake consisting of the filtered solids (suspended solid and body feed filter aid):

$$H_2 = 6.26 \times 10^{-9} \frac{\mu \alpha_2}{gd} QW_2 . \quad . \quad . \quad . \quad . \quad (6)$$

since,

$$W_2 = C_D Qt \times \frac{8.33}{10^6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where:

8:33 = the bulk density, $\underline{d}$, of water, and

10^6 = the conversion factor to change $\underline{C}_D$ in ppm to C_D as a weight fraction,

$$H_2 = 6.26 \times 10^{-9} \frac{\mu \alpha_2}{gd} \left(\frac{C_D Q^2 t \ d}{10^6}\right) . \, . \, . \, (8)$$

and

$$K_4 = 6.26 \times 10^{-9} \frac{\mu \alpha_2}{gd} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

It may be seen that $\underline{K}_4$ also varies with temperature to the same extent as does $\underline{K}_3$. Figure 1 is adapted from figures 6 and 7 of a recent paper[3] to show the relationship between α_2 and $\underline{K}_4$ as functions of C_{FE} / C_D.

A modified form of the diatomite filter equation can be written involving the average specific resistance, α, instead of $\underline{K}_3$ and $\underline{K}_4$:

$$H = 6.26 \times 10^{-9} \frac{\mu Q}{gd} \left[\alpha_1 W_1 + \alpha_2 \frac{C_D Qtd}{10^6} \right] . \, (10)$$

The use of average specific resistances α_1 and α_2 in the diatomite filtration equation corresponds to established filtration practice. Also, it relates the resistance of the clean filter aid in the precoat to that of the dirty filter aid in the rest of the cake.

Acknowledgement

This work was supported by the Iowa Engineering Experiment Station, Iowa State University, in part through funds made available by Research Grant WP-00196 from the Water Supply and Pollution Control Section, National Institutes of Health, U.S. Public Health Service.

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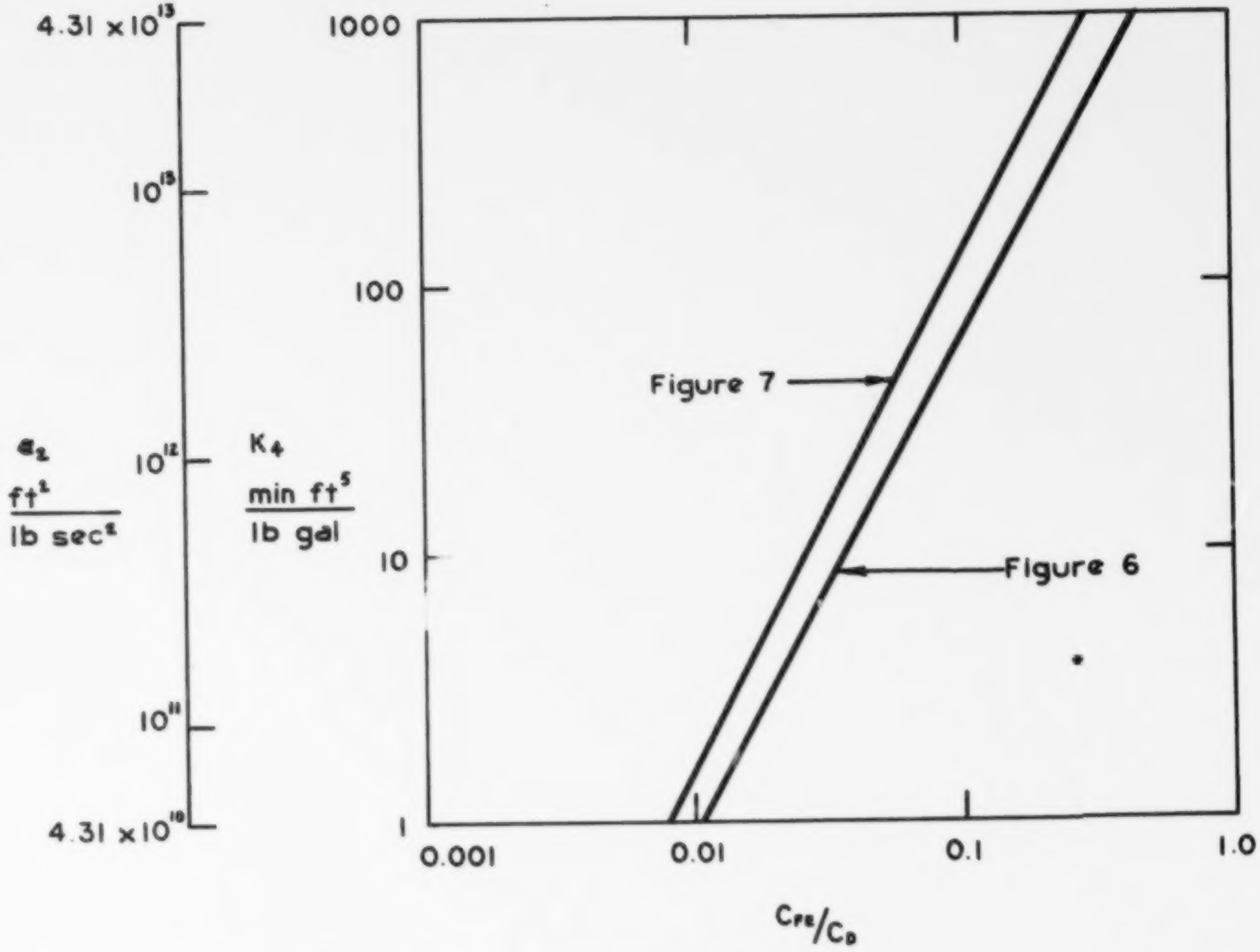

Fig. 1. Comparison of a_2 and K_4 as functions of C_{FE}/C_D.
Figures "6" and "7" in the above refer to a recent publication[3].

PART III

HYDRAULIC AND PARTICLE SIZE CHARACTERISTICS OF SOME DIATOMITE FILTER AIDS

James H. Dillingham
E. R. Baumann

Progress Report

HYDRAULIC AND PARTICLE SIZE CHARACTERISTICS OF SOME DIATOMITE FILTER AIDS

by

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Public Health Service Research Fellow

and

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Professor of Civil Engineering

United States Public Health Service
Research Grant WP-00196

Project 509-S, Municipal Diatomite Filters

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January 15, 1964

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HYDRAULIC AND PARTICLE SIZE CHARACTERISTICS OF SOME DIATOMITE FILTER AIDS

by

James Hugh Dillingham

and

E. R. Baumann

INTRODUCTION

BACKGROUND

Some of the material suspended in water is removed when it goes through a diatomite filter. The amount removed depends on a number of variables: the water, the filter aid, the filter, and how the filter is operated. Each of these variables must be considered in the design of a diatomite filter plant. The final filter design should be based on the combination of body feed, terminal head loss, and rate of filtration that will give a finished water of the required quality at least cost[5].

A diatomite filter removes material in at least two principal ways. Particles larger than the openings in the filter cake simply cannot pass through the cake, and are thus mechanically strained from the water. Particles smaller than the openings in the filter cake may also be removed. Examples of such small particles are bacteria, macromolecules, color, and colloidal materials, such as clay. Even dissolved solids may be removed. A commonly accepted explanation of the removal of these colloids is based on electrokinetic phenomena. When the colloids in the water have the same charge as the filter aid particles, the colloids are repelled by other colloids, body feed particles, and the filter cake. Particles larger than the openings in the filter cake are removed by straining, but the smaller particles pass through the cake. When the colloids and the filter aid particles are oppositely charged, the colloids are attracted by the body feed particles and the filter cake. Some of the particles smaller than the openings in the cake are thus held tightly enough to be removed.

Ordinary diatomite filter aids and most of the colloids in natural water supplies have a negative surface charge. Filter aids with a positive surface coating remove negative colloids. Effective removal by the use of positively coated filter aids of negatively charged turbidity, color, and coliform bacteria has been demonstrated[6]. Proportionally greater removal of these materials is obtained using "coated" Celite 545 than is obtained using much finer, untreated Hyflo Super-Cel (figures 1, 2, 3).

More material can be removed from any water containing suspended solids by using finer grades of filter aid, but more energy (head loss) is necessary to force the water through the finer cake at the same flow rate. This increased energy requirement results in higher pumping costs. It may be advantageous sometimes to use a positively coated filter aid rather than a finer grade to achieve higher removal of negative colloids. The savings in pumping costs may justify the increased cost of the filter aid which must be chemically treated either in production or just before use.

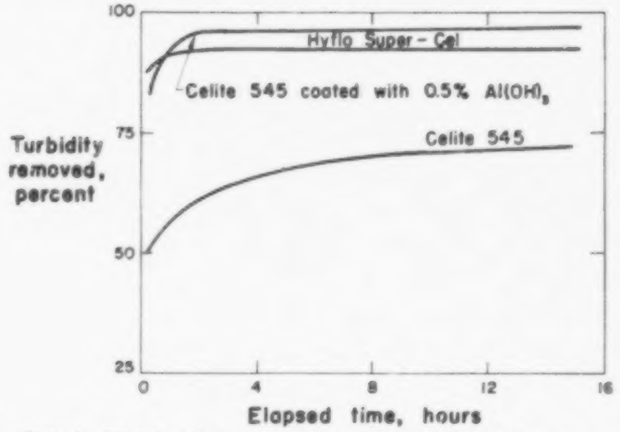


Figure 1 Effect of an electropositive coating of aluminum hydrate on turbidity removal from Raritan River water (5)

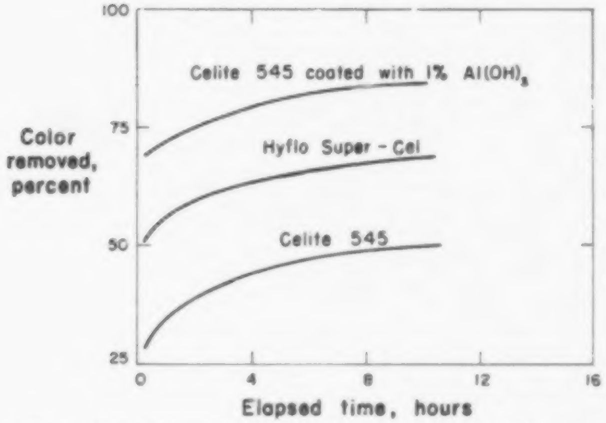


Figure 2 Effect of an electropositive coating of aluminum hydrate on color removal from Raritan River water (5)

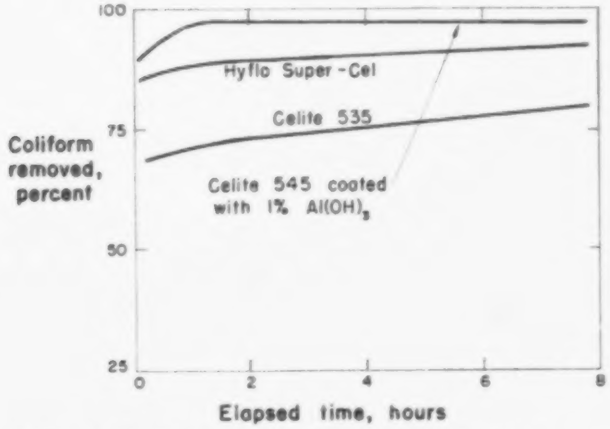


Figure 3 Effect of an electropositive coating of aluminum hydrate on coliform removal from Raritan River water (5)

Tests should be made with a small pilot plant at the raw water source to determine the various optimums involved: optimum body feed, optimum head loss, optimum volume of filtrate per pound of diatomite, optimum volume of filtrate per unit cost[12]. Some laboratory tests could also be made with a small laboratory filter. Various grades of positive and negative filter aids could be used to determine which filter aids would give adequate solids removal and filter cake permeability. A small "bomb" filter may be used for this purpose[9]. With the data thus obtained, along with cost data pertaining to power, labor, filter aids, and interest, several grades of filter aid can be chosen. A filter plant can then be designed, and a plant so designed should produce acceptable water at the most economical cost[5, 11].

The filter aid is important in the operation of a filter plant. Much depends on the characteristics of the filter aid and its performance in the filter. Poor performance results in excessive filtration costs, the production of poorer quality water, and might indicate a need for use of a different filter aid. To choose a filter aid with the desired characteristics and to evaluate such characteristics, the engineer will need:

A standard method of specifying the characteristics of a filter aid;
Knowledge of the expected lot to lot variation in the characteristics of a given grade of filter aid from a particular manufacturer; and
Knowledge of the allowable general range of each characteristic of the filter aid for a specific application.

FILTER AID PROBLEMS

After the plant has been designed and is in operation, the overall economy of the plant may be altered and the plant may become inefficient in operation. Two possible explanations of the changes in the filtering and hydraulic characteristics of the filter aid are:

Particle size degradation (breaking up of the filter aid particles into smaller particles) as the filter aid passes through such various units of the plant as pumps, feeders, and mixers;
Changes in the filtering and hydraulic characteristics of the filter aid from one shipment to the next.

Both of these have been experienced in recent research conducted at Iowa State University.

Both must be corrected before an engineer can be assured that a filter aid will perform as expected. The problem of degradation might be handled by using a coarser filter aid to compensate for the particle size degradation. This may not be satisfactory, however, because the amount of degradation probably varies as the run progresses. A better approach would be to minimize degradation as much as possible by the wise placement of feeders and pumps. The filter aid should not pass through the pumps, but should be placed in the flow on the discharge side. More research is needed to determine quantitatively just which units and processes in a plant tend to degrade the filter aid particles.

Good standard specifications would aid the engineer in evaluating and eliminating the variations in filter aids. These specifications could be of great value in the effective control of the operation of a plant.

By requiring that a filter aid meet certain specifications, a purchaser could be assured of the quality of the filter aid. A specification for each of the properties that are important in the use of a filter aid in municipal water supplies should be included in overall filter aid specifications. As a minimum, specifications are needed for the type of filter aid, some characteristic representative of particle size, its permeability, and its surface charge. Filter aid specifications must include or specify standard tests to be used to determine each of these characteristics. The tests must be standardized to insure that different investigators will arrive at the same values for the filter aid characteristics when they are using aliquots of the same filter aid.

The filtering characteristics of a filter aid will depend mainly on:

The type of filter aid, such as diatomite, perlite, crystal-flo, etc.;
The particle size distribution of the filter aid;
The permeability of the filter aid, and
The surface charge of the filter aid.

As pointed out, overall filter aid specifications should include specifications for each of these characteristics. Filter aids other than diatomite were not tested in this study, and no tests were made as to surface charge. The tests were concerned with particle size and permeability of diatomite filter aids. Since both particle size and permeability are determined hydraulically, they will be classed as hydraulic rather than filtering characteristics. However, the filtering characteristics and the hydraulic characteristics of a filter aid are not independent of each other.

OBJECTIVE

The main purpose of this report is to give some data pertaining to the hydraulic characteristics of commercial grades of diatomite, data that could be useful in the writing of filter aid specifications. The specific objectives were:

To evaluate the reproducibility and relative simplicity of two ASTM (American Society for Testing and Materials) methods of determining the particle size of diatomite filter aids;
To determine the particle size distribution of different commercial grades of diatomite and of different lots of the same grade of diatomite;
To determine K_3 values of different grades of diatomite and of different lots of the same grade of diatomite. (K_3 is a constant for a given grade of diatomite and is inversely proportional to its coefficient of permeability);
To compare the K_3 values of different commercial filter aids with their corresponding particle size distributions.

REVIEW OF LITERATURE

PARTICLE SIZE

Different methods for determining the particle size distribution of diatomite filter aids do not, in general, give comparable results. For this reason, a standard method of determining particle size distributions of filter aids is essential, but no such standard is used or accepted in the water works industry. Such a method should be relatively simple and inexpensive. At the present time, there are also no particle size standards for diatomite.

Two ASTM methods of particle size analysis of soils were used in this study[1,2]. One is the 1939 ASTM method D422-39 for grain-size analysis of soils[2]. The portion of this test pertaining to sub-sieve sizes is a sedimentation analysis using an hydrometer. The theory of the method is based on Stokes Law.

The current method for particle size analysis of soils is the 1961 ASTM tentative method (D422-61T) for grain-size analysis of soils[1]. This test is a revision of ASTM D422-39, and the procedures are almost identical. The major difference in the two tests involves the dispersing agent used. ASTM D422-61T also encourages the use of air dispersion to get the sample into suspension, since air dispersion does not tend to degrade the particles as much as mechanical mixing.

There is little information available from filter aid manufacturers regarding the particle size distribution of their current filter aid grades. Principal diatomite filter aid producers in the United States are Eagle-Picher Company, Cincinnati; Great Lakes Carbon Corporation, Los Angeles; Johns-Manville Corporation, New York. These three manufacturers use different methods for determining filter aid particle size. No particle size distribution curves were found in bulletins or brochures published by either the Great Lakes Carbon Corporation or the Eagle-Picher Company. Some particle size distribution curves are included in one of the brochures printed by the Johns-Manville Corporation[10], but the particle size test used was not one of the standard tests used in this study.

Some research was done in 1950 with particle size and permeability of Celite 535 filter aid[3]. Externally applied mechanical pressure degraded the filter aid particles and decreased its permeability. The inference was drawn that hydraulic pressure would have similar effects on filter aids. The method used to determine particle size distribution was basically the same as the ASTM tests mentioned earlier. Methods of defining the hydraulic characteristics of filter aids that could be used in a filter aid specification were sought; however the methods investigated were not as simple as the methods investigated and reported herein.

PERMEABILITY

ASTM standard methods have been developed for the determination of permeability of soils, but there are no standards for determining the permeability of diatomite. Some soil procedures were used to determine permeability when the effect of mechanical compression on filter aids were studied[3]. But these procedures are not as convenient as the proposed procedure used in this study for application to diatomite filtration. The determination of the permeability of diatomite filter aids is confined to the evaluation of K_3 coefficients in the diatomite filtration equation[4, 11]:

$$H = K_3 Q W_1 + K_4 C_D Q^2 t \quad \ldots\ldots \quad (1)$$

where : H = total head loss through the filter cake (ft)
C_D = concentration of body feed (ppm)
K_3 = permeability coefficient for the clean precoat ($ft^5 min/\#gal$)
K_4 = permeability coefficient for the body feed layer ($ft^5 min/gal^2$)
Q = rate of flow (gpm/ft^2)
T = time of filtration (min)
W_1 = weight of precoat ($\#/ft^2$)

A slightly modified development of the equation is presented here. If conditions in the filter are such that Darcy's law holds, then,

$$Q = K_p H/L \quad \text{or} \quad H = QL/K_p = KQL$$

where: K_p = coefficient of permeability (gpm/ft^2)
L = thickness of porous layer (ft)
K = $1/K_p$

The total head loss through the filter cake can be divided into two parts— the head loss through the precoat and the head loss through the body feed layer. It is assumed that these two head loss contributions are independent of each other. The head loss through the filter septum is assumed to be negligible. In the following, the subscript 1 refers to the precoat terms, and the subscript 2 refers to the body feed terms. Accordingly,

$$H = K_1QL_1 + K_2QL_2 \quad . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

Since density is defined in units of weight per unit volume, it follows that

$$L_1 = W_1/d_1, \quad L_2 = W_2/d_2 \quad . \; . \; . \; . \; . \; (3)$$

where: W = weight of material in the appropriate layer of the filter cake (#/ft^2)
d = in place bulk density of the appropriate layer (#/ft^3)

but

$$W_2 = (C_D + C_{SS})(10)^{-6} Qtd_w \quad . \; . \; . \; (4)$$

where: C_D = concentration of body feed (ppm)
C_{SS} = concentration of suspended solids (ppm)
t = time (min) elapsed since beginning of filter run
d_w = density of water (#/gal).

Substitution of equations 3 and 4 into equation 2 yields:

$$H = K_1QW_1/d_1 + K_2Q(C_D + C_{SS})(10)^{-6} Qtd_w/d_2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (5)$$

The development is now complete, since equations 5 and 1 are identical when

$$K_3 = K_1/d_1,$$

$$K_4 = K_2(1 + C_{SS}/C_D)(10)^{-6} d_w/d_2 \quad . \; . \; . \; (6)$$

When clean water is passed through a precoat layer of filter aid with no body feed layer present, equation 1 reduces to $H = K_3QW_1$. Under these conditions, K_3 can be evaluated experimentally from a plot of H vs QW_1. At a constant temperature, K_3 is constant for a given filter aid and is representative of the permeability of the filter aid. Actually, K_3 is inversely proportional to the coefficient of permeability. Both K_3 and K_4 are dependent on the viscosity of the water, and therefore dependent on the water temperature. Accordingly, all values of K_3 and K_4 should be expressed at a standard temperature, 20°C for example, for purposes of comparison.

A K_3 or K_4 value expressed at temperature "T" can be changed to a corresponding value expressed at 20°C. This is done by simply multiplying the K_3 or K_4 value by the ratio of the viscosity of water at 20°C to the viscosity of water at temperature "T" as follows:

$$K_3 = (K_3)_T\, n/n_T, \quad K_4 = (K_4)_T\, n/n_T$$

where: K_3 = K_3 at 20°C
K_4 = K_4 at 20°C
$(K_3)_T$ = K_3 at temperature "T"
$(K_4)_T$ = K_4 at temperature "T"
n = viscosity of water at 20°C
n_T = viscosity of water at temperature "T"

The viscosity of water at 20°C is 1.009 centipoises If we take n to be 1.00 centipoise,

$$K_3 = (K_3)_T/n_T, \quad K_4 = (K_4)_T/n_T \quad . \; . \; (7)$$

Notice that n_T must be substituted into equation 7 as centipoises because n was in centipoises.

SURFACE CHARGE

The surface charge on diatomite filter aids used for water filtration is ordinarily negative, but the charge can be changed to positive during manufacture or just before use by coating the filter aid with electropositive coatings. Iron and aluminum salts and cationic polyelectrolytes have been used, but iron salts are not as effective as aluminum salts and cationic polyelectrolytes[13].

When water is filtered through a porous medium, an electrical potential difference, called a streaming potential, is developed between the upstream and downstream sides of the filter. The streaming potential is positive if the upstream potential is positive with respect to the outlet potential. The streaming potential can be measured by placing one electrode in the inlet stream and another in the outlet stream and measuring the potential difference. The streaming potential becomes vanishingly small as the concentration of ions in the water increases. This is due to the decreasing resistivity of the water as the ion concentration increases. The ions provide a path for electrons to flow, and this flow of electrons dissipates the streaming potential.

A value of zeta potential can be determined from streaming potential data. However, the value of zeta potential will not, in general, be comparable with a corresponding value of zeta potential determined by electrophoresis[13]. The electrical field that the filter aid is placed in for electrophoretic measurements seems to be strong enough to separate most of the surface coating from coated filter aids. The resulting zeta potential determined by electrophoresis would then be negative rather than positive. However, the zeta potentials determined by streaming potential measurements are positive for a positively coated filter aid. The hydrodynamic forces present under the conditions of a streaming potential test then are not strong enough to separate the coating from the particle.

If a positive filter aid is necessary, a positive surface charge should be specified. If a positive filter aid is not needed, no charge specification is needed because diatomite filter aids are normally electronegative. If a positive filter aid is specified, the filter aid should be tested to determine if it has the electropositive filtering characteristics desired. A streaming potential test would be sufficient for this purpose[13]. Specification of zeta potential would not be necessary because zeta potential is more positive than the streaming potential when the streaming potential is positive; and zeta potential is more negative than the streaming potential when the streaming potential is negative. The criteria to be used to determine if a filter aid had positive filtering characteristics could be that the measured streaming potential be equal to or greater than some specified value, say +5 millivolts.

The streaming potential test would have to be performed using a standard water, such as distilled or deionized water, to be useful in a surface charge specification. The water used must have a very small concentration of dissolved minerals to prevent dissipation of the streaming potential before it could develop.

Electrophoresis cannot be used as a test to determine effective surface charge of a filter aid because an electrical field seems to separate the positive surface coating from the filter aid[13].

LABORATORY APPROACH

PARTICLE SIZE

Three series of particle size tests, Series I, II, and III, were completed. Information about each of the diatomite samples tested for particle size and K_3 values in this study includes (table I):

The commercial name of the filter aid;
A lot designation for each lot of the same grade;
The manufacturer;
The source of the sample (Three of the samples were supplied by the U. S. Army Engineer Research and Development Laboratories, ERDL, Fort Belvoir, Virginia. The remaining samples were supplied by the manufacturers.)
How the sample is referred to in the text; and
Which of the samples make up the samples tested in each of the three series of particle size tests I, II, and III.

Series I

All Series I particle size tests were performed on C535/A (table I). The purposes of the Series I tests were:

To determine how long and at what pressure the air dispersion tube should be operated;
To evaluate the repeatability of the two ASTM tests;
To determine what sample weight to use in the tests; and
To evaluate the relative simplicity of the two ASTM methods and how the results of the two methods compare.

The choice of the dispersion time and pressure was based on the author's best judgment after inspection of the air dispersion tube in operation at various pressures. A combination of dispersion time and pressure that would disperse the sample adequately, but not too vigorously or too long, was desired. Virgorous dispersion tended to degrade the filter aid particles, and the test was designed to eliminate particle size degradation as much as possible. A dispersion time of 5 minutes at a pressure of 5 psi was used for all particle size tests performed. The volume of the diatomite slurry in the sedimentation cylinder was brought to 350 ml for dispersion. In Series I sample weights of 50, 30, and 20 grams were used. Each test was repeated from two to eight times. Both ASTM methods were used in Series I.

Series II

In Series II particle size tests were performed on diatomite samples in Table 1 from sources a and b, excluding C535/A. The purposes of the Series II tests were:

To determine the particle size distribution for each of the 19 commercial grades supplied by their manufacturer as representative of their commercial standard;
To supply information, in addition to the Series I results, to be used in evaluating the repeatability of the ASTM D422-61T method; and
To supply information, in addition to the Series I results, to be used in comparing the results of the two ASTM methods.

Four particle size tests were made on each of the samples of Series II — three using the ASTM D422-61T method and one using the D422-39 method. These four tests were numbered from 1 to 4.

TABLE I. FILTER AID SAMPLES

Grade	Lot	Source	Test Series	Referred to in test as
Commercial Grades of Johns-Manville Corp.				
Celite 560		a	II	C560
Celite 545		a	II	C545
Celite 535	A	a	I	C535/A
Celite 535	B	b	II	C535/B
Celite 535	C	c	III	C535/C
Celite 535	D	c	III	C535/D
Celite 503		a	II	C503
Hyflo Super-Cel		a	II	
Standard Super-Cel		b	II	
Filter-Cel		b	II	
Commercial Grades of Great Lakes Carbon Corp.				
Dicalite 5000		a	II	D5000
Dicalite 4200	A	a	II	D4200/A
Dicalite 4200	B	c	III	D4200/B
Speedex		a	II	
Speedplus		a	II	
Speedflow		b	II	
Dicalite 115		b	II	D115
Commercial Grades of Eagle-Picher Co.				
Celatom FW-60	A	d	III	FW-60/A
Celatom FW-60	B	d	III	FW-60/B
Celatom FW-60	C	d	III	FW-60/C
Celatom FW-60	D	d	III	FW-60/D
Celatom FW-60	E	b	II	FW-60/E
Celatom FW-50	A	d	III	FW-50/A
Celatom FW-50	B	d	III	FW-50/B
Celatom FW-50	C	d	III	FW-50/C
Celatom FW-50	D	d	III	FW-50/D
Celatom FW-20		b	II	FW-20
Celatom FW-20	A	d	III	FW-20/A
Celatom FW-20	B	d	III	FW-20/B
Celatom FW-20	C	d	III	FW-20/C
Celatom FW-20	D	d	III	FW-20/D
Celatom FW-14		b	II	FW-14
Celatom FP-4		b	II	FP-4
Celatom FN-2		b	II	FN-2

a-Supplied prior to Jan. 1962　c-Supplied by ERDL
b-Supplied about Oct. 1962　d-Supplied Jan. 1963

Series III

In Series III all particle size tests were performed on diatomite samples in Table I from sources c and d . The purpose of these tests was to secure information to be used in evaluating the variation in particle size distribution between lots of the same grade of diatomite. Only the ASTM D422-61T method was used to determine particle size.

PERMEABILITY: K_3

None of the K_3 values obtained from tests made before modification of the test apparatus by installation of a precoat pot were reliable, and all were discarded. Many of the first tests made after the addition of the precoat pot were also unreliable. K_3 results obtained after some refinements were made in the operating procedure were very good. These are the results reported. The permeability tests were made to determine K_3 values for each diatomite sample listed in Table 1 in order to evaluate the following:

The repeatability of K_3 values obtained with the EK filter;
The variation of K_3 in commerical grades of diatomite filter aids;
The variation of K_3 between lots within the same grade of diatomite; and
A correlation between the K_3 value for a filter aid and some characteristic of its particle size.

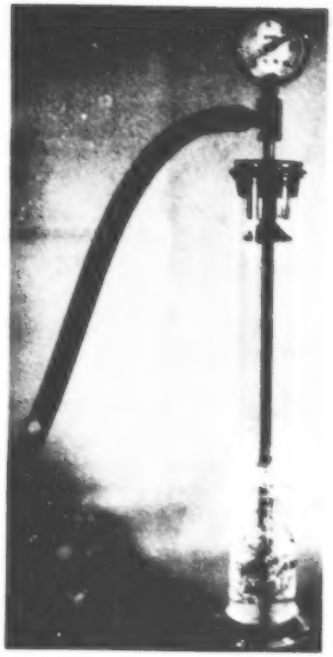
LABORATORY APPARATUS

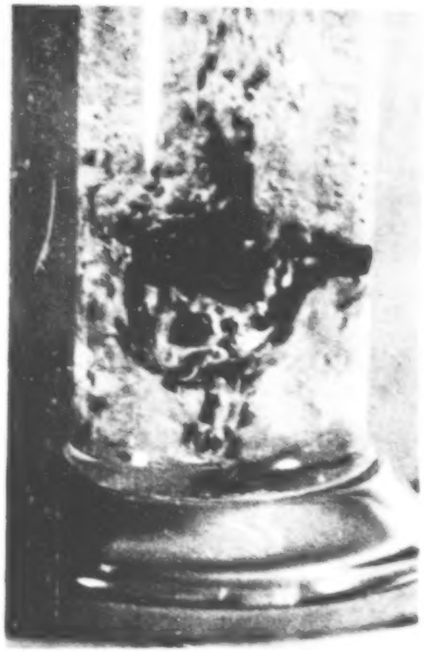
PARTICLE SIZE DISTRIBUTION

In the hydrometer method of particle size analysis, a sample of filter aid is suspended in water in a sedimentation cylinder. A dispersing agent is used to prevent agglomeration of the filter aid particles. The filter aid is then allowed to settle to the bottom of the cylinder over a 24 hour period. The specific gravity is measured periodically with a hydrometer. The average particle size still in suspension at the time of the hydrometer reading can be related to the hydrometer reading by Stoke's law. An hypothesis in the derivation of Stoke's law is that a single, spherical particle settles in an infinity of liquid. The conditions of the particle size test do not satisfy this hypothesis. Nevertheless, the results obtained using Stoke's law are useful and reproducible. The apparatus required in the test includes[1, 2]:

A constant temperature water bath or a constant temperature room;
A series of sedimentation cylinders;
An hydrometer;
A thermometer;
An air dispersion tube; and
A beam balance.

The water bath was a galvanized metal tank, 24 inches long by 14 inches wide by 16 inches deep. A Fenwal Thermoswitch was mounted in the wall of one end of the tank about three inches from the bottom. A small overflow was constructed in the tank. Cold water was allowed to trickle in at the top to prevent the water from getting too warm. Should the water in the bath become too cool, the thermoswitch would close an electrical circuit and activate a 1000-watt heating coil in the bottom of the tank. Although the tank was not insulated, the water temperature variation in the tank never exceeded ± 0.3°C. To counteract the buoyancy of the sedimentation cylinders, their tops were held steady in the





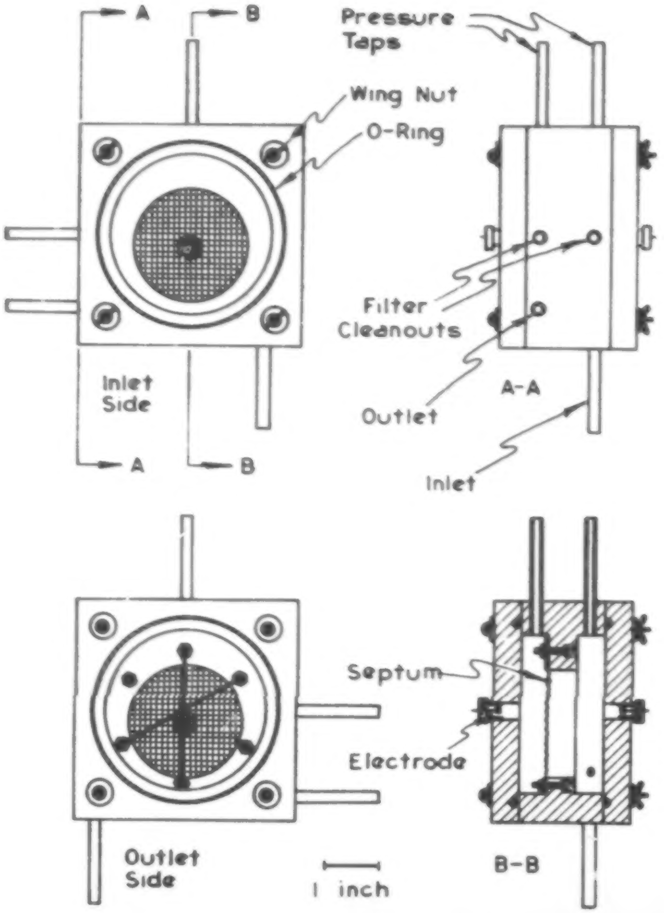


Fig. 4. at left, above. Air dispersion tube fitted into 1000 *ml sedimentation* cylinder (Diatomite samples were dispersed for 5 min at 5 psi.

Fig. 5. at right, above. Bubbling action at bottom of air dispersion tube operated in 350 ml water at 5 psi

Fig. 6, at right. Scaled drawing of EK filter[13].

tank by brackets.

The diatomite samples were dispersed with the aid of an air dispersion tube[7]. The air dispersion tube fits into a sedimentation cylinder, and the diatomite sample is dispersed by compressed air jets (figures 4, 5). Air dispersion does not tend to degrade the diatomite as much as mechanical dispersion.

The ASTM 152H type hydrometer used was calibrated to read in grams of soil (specific gravity, 2.65) in suspension in water at 20°C.

PERMEABILITY: K_3

The small electrokinetic filter (EK filter) was used to determine K_3 values for the various grades of diatomite[13]. The filter was designed originally to determine streaming potentials (figure 6). However, no streaming potential data were taken in this study.

The EK filter is a small pressure filter with a 2 inch diameter septum in a vertical plane. The filter housing is made entirely from plexiglass. The septum used at first was made of a plastic filter cloth, but the plastic was later replaced by stainless steel mesh. The flow enters the filter tangentially, creating a rotary flow pattern in the filter on the inlet side of the septum. The increase in flow velocity resulting from the rotation is sufficient to keep the diatomite in suspension until it is deposited on the septum. The electrodes mounted on each side of the filter are not necessary for determing K_3 values; they were used by Oulman to measure streaming potentials.

The EK filter apparatus included a source of water, a pump to supply pressure, a filter housing and septum, a manometer for measuring head loss across the septum, and a flow measuring and control device (figure 7, 8). A small precoat pot was supplied for precoating the septum. The apparatus permitted measurement of flow rate and head loss through a precoat of known weight. A polyethylene waste can (8 gallons) served as a water supply tank. Connecting tubing consisted of 1/4 inch OD glass tubing, 1/4 inch ID Tygon tubing, and 1/4 inch OD copper tubing. These sizes were small enough to prevent the deposition of diatomite in the lines.

A centrifugal pump was used. The flows used in the system were less than one percent of 7 gpm, the pump capacity when operating against zero head. As a result, the temperature of the water increased about 3°C as it flowed through the plant. Flow was controlled with a small needle valve.

A bromoform manometer (specific gravity of bromoform, 2.85 at 25°C) was used to determine the head loss through the filter cake.*

After the precoat pot was added, the precoat could be applied to the septum without first passing through the pump (figure 9). The precoat pot was a plexiglass cylinder, three inches in diameter and 3 3/4 inches deep with a plexiglass bottom. A 1 1/2 inch ID steel section was attached to the top of the pot with epoxy resin. This steel section was fitted with a rubber O-ring and a steel cap to form a pressure tight seal. The precoat pot was so designed that diatomite could be placed into

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*The operator must be careful when using the bromoform manometer, since bromoform has anesthetic properties similar to chloroform, and it is a solvent for the plexiglass filter housing.

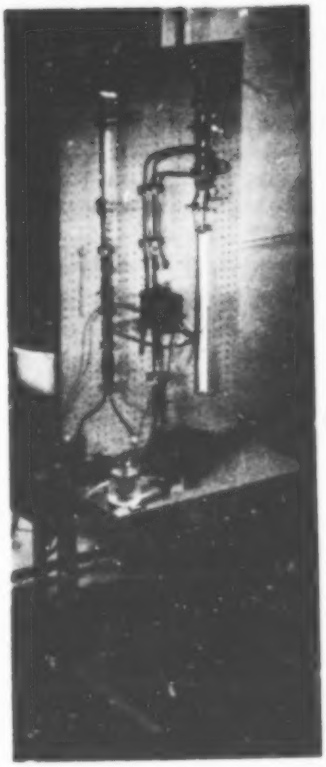


Fig. 7. EK filter plant ready for use[13].

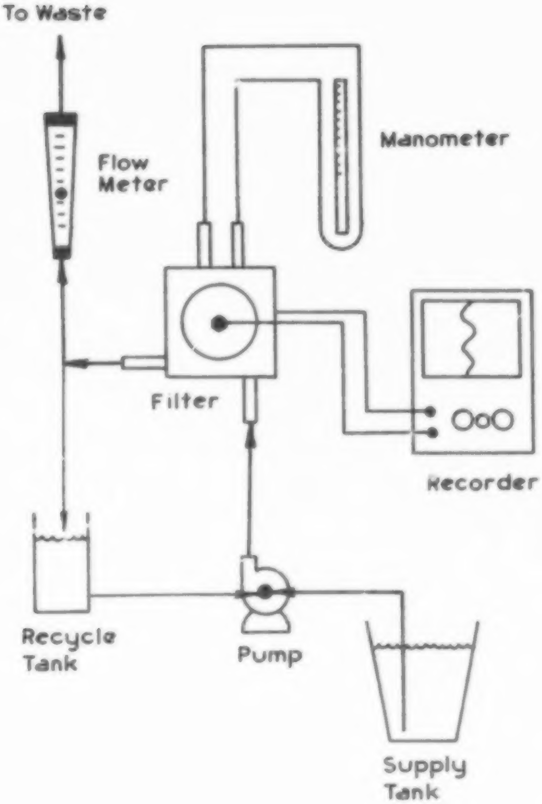


Fig. 8. Flow diagram of EK filter plant[13].

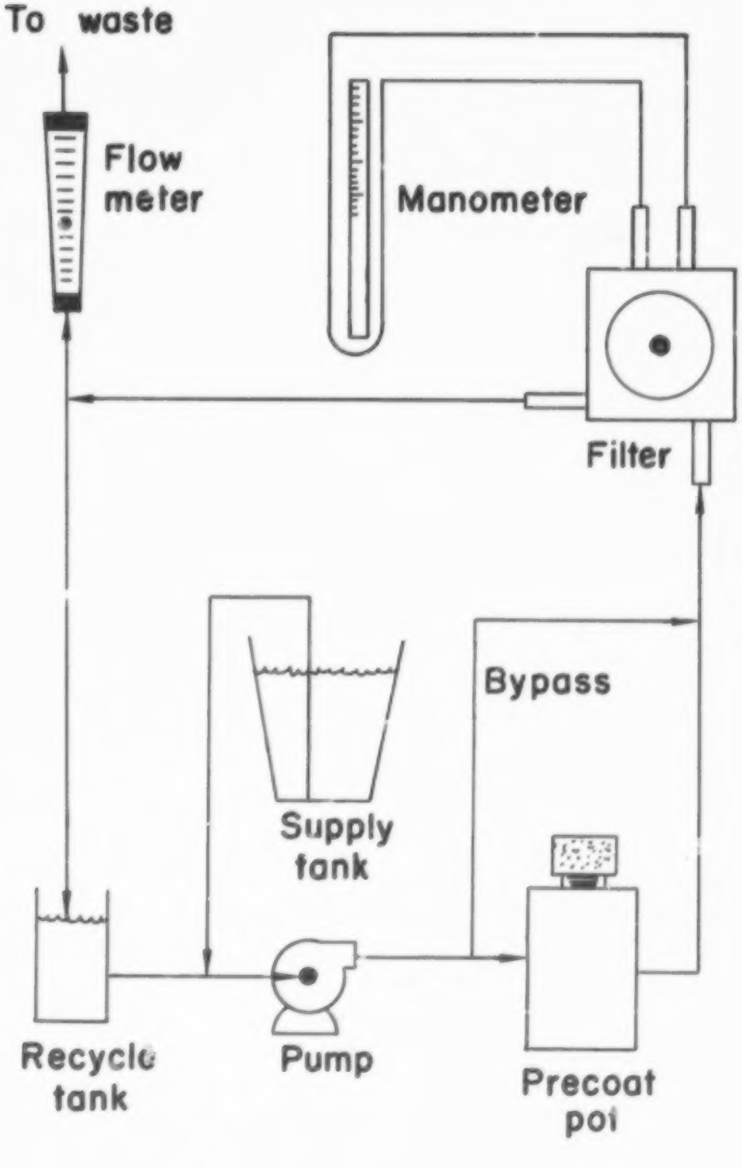
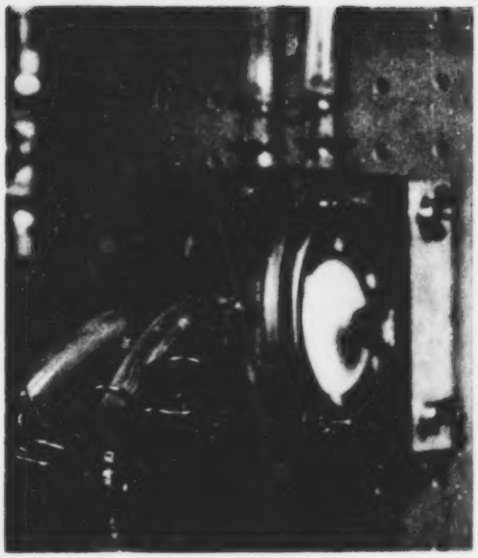


Fig. 9. Flow diagram of EK filter plant after precoat pot was added.



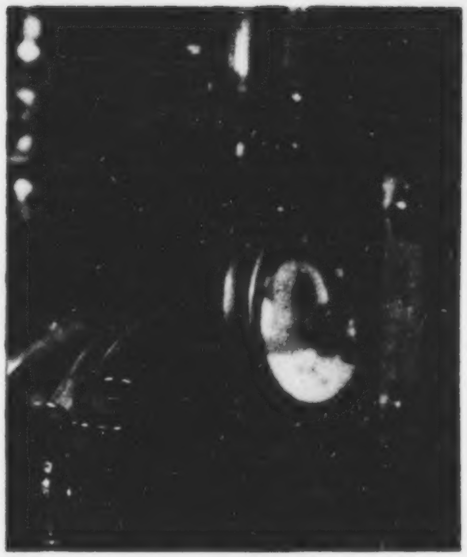


Fig. 10, left. Appearance of well-formed precoat in filter[13].

Fig. 11, right. Appearance of precoat that has dropped from septum at end of filtering operation[13].

it with a minimum amount of effort in a minimum amount of time. The diatomite was kept in suspension in the precoat pot by a magnetic bar rotated by a magnetic stirrer setting beneath the precoat pot.

LABORATORY PROCEDURES

PARTICLE SIZE

The procedures used for making particle size tests during this study were similar for both ASTM D422-39 and ASTM D422-61T. The only difference in the two methods, as used in this study, was the type and amount of dispersing agent used. Sodium silicate was used in the D422-39 procedure, but sodium hexametaphosphate was used in the D422-61T procedure. The composite correction method of correcting hydrometer readings was used with both dispersing agents because it simplifies the procedures considerably[1]. An air dispersion tube was used as the dispersion device. Specific gravities of the diatomite samples were determined by the pycnometer method used for soils. Hygroscopic moisture was found to be negligible for all grades of diatomite applicable to municipal water filtration.

Composite correction

The composite correction is a value added to the hydrometer reading to compensate for:

The use of a dispersing solution rather than distilled water as the suspending medium;
Deviation of the temperature from 20°C, the temperature at which the hydrometer was calibrated; and
Reading of the hydrometer at the top rather than at the bottom of the meniscus.

A curve of composite corrections for the hydrometer used in this study was determined according to the instructions in D422-61T. The curve is a plot of the negative of hydrometer (ASTM 152H hydrometer) readings vs. temperature for the suspending medium containing no diatomite sample (figures 12, 13). The composite correction is added to the actual hydrometer reading to determine the percent of diatomite still in suspension. This is equivalent to the subtraction of the hydrometer reading of a "blank" from the corresponding hydrometer reading of the sample. More composite correction observations were taken than suggested by the instructions in D422-61T.

Dispersion of Sample

The procedure for preparing and dispersing the sample was simplified by using the air dispersion tube. Except for some minor changes, the procedure is exactly that of ASTM D422-61T:

Weigh out sample of diatomite and place it in sedimentation cylinder.
Cover sample with appropriate quantity of dispersing solution (125 ml sodium hexametaphosphate solution for ASTM D422-61T or 20 ml sodium silicate solution for ASTM D422-39). Add enough distilled water to cover entire sample. Soak sample 18 hr.
After soaking, add enough distilled water to fill cylinder to 350 ml.
Disperse sample 5 min at 5 psi with air dispersion tube.
After dispersion, wash any diatomite that adhered to dispersion tube into cylinder with a wash bottle.

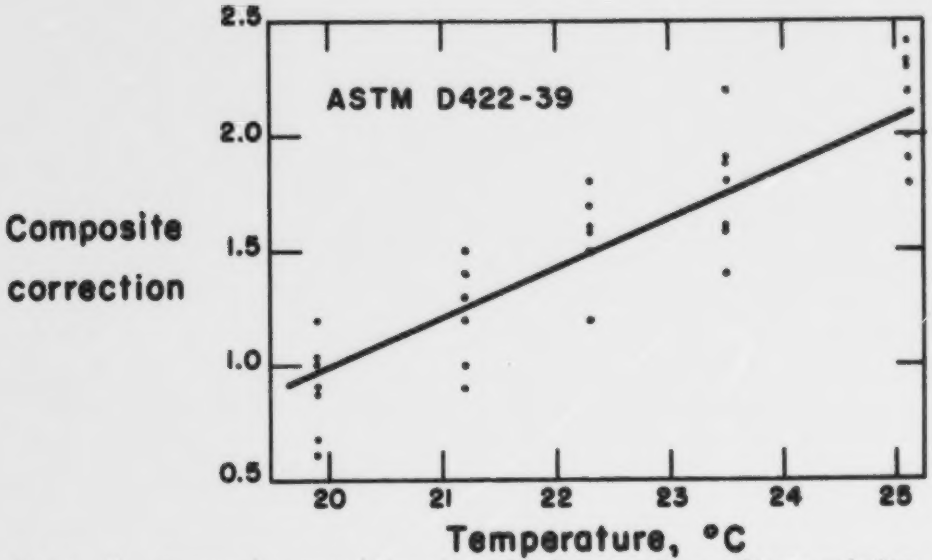


Figure 12. Composite correction curve for 20 ml sodium silicate solution per 1000 ml of suspension. Curve is valid only for hydrometer used in determining it.

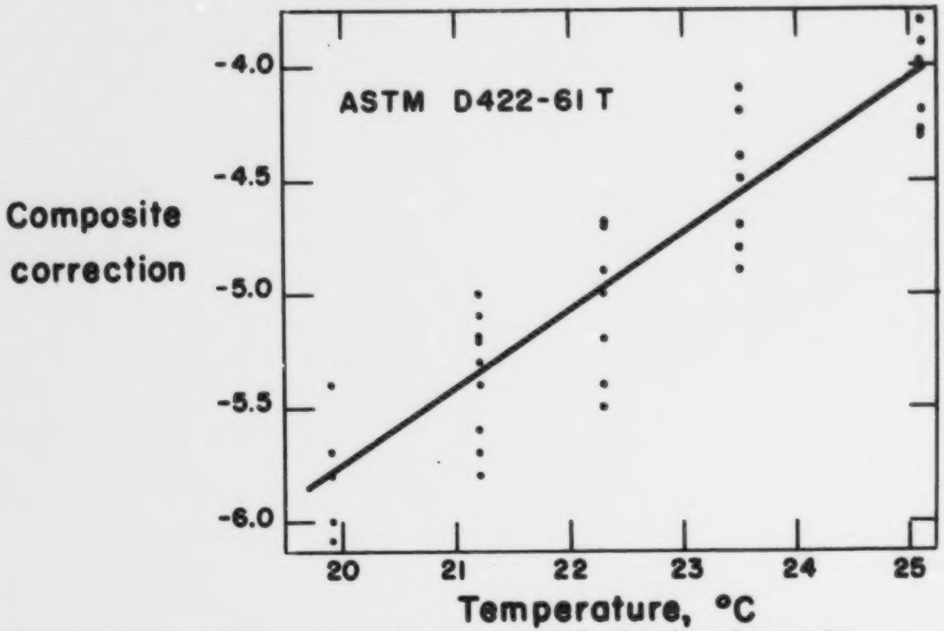


Figure 13. Composite correction curve for 125 ml sodium hexametaphospate solution per 1000 ml of suspension. Curve is valid only for hydrometer used in determining it.

Remove dispersion tube and fill cylinder to 1000 ml mark using distilled water. Water used should be at temperature that will prevail during hydrometer test.

Hydrometer Test

No change was made in the hydrometer test procedure of ASTM D422-61T. Hydrometer readings were taken at 1, 2, 5, 15, 30, 60, 250, and 1440 min. The sedimentation cylinder was carefully placed in the water bath immediately after the 2 min. reading. A typical particle size data sheet (Data sheet 1) and formulas used in the particle size calculations are in Appendix C. The calculations necessary to determine the points of the particle size distribution plot (percent finer vs. particle size in microns) are made on the data sheet.

PERMEABILITY: K_3

The EK filter plant requires three basic operations just as in all diatomite filter plants:

Precoating is the operation of placing the diatomite onto the septum to form the precoat;
Filtering is the operation of using this precoat and the body feed layer that builds up on it as the filtration medium;
Backwashing is the operation of removing the filter cake at the end of a filter run.

To determine K_3, clean water containing no body feed is passed through a clean precoat. Under these conditions, there is no body feed layer present, only the precoat. Thus, the second term on the right hand side of equation 1 reduces to zero, and equation 1 reduces to $H = K_3QW_1$. K_3 is then the slope of the arithmetic plot of H vs. QW_1 in appropriate units (ft^5 min/# gal at 20°C in this study)[4].

Only the precoating operation was changed after the precoat pot was added. Before the precoat pot was added, the diatomite sample, in the form of a slurry, was placed in the recycle tank. Since the recycle tank was downstream from the pump (figure 8), all of the diatomite passed through the pump before reaching the septum. With the addition of the precoat pot, however, only the small amount of diatomite that passed through the septum at the start of the precoating operation passed through the pump (figure 9).

It was found that a thorough cleaning of the apparatus was required between each run to obtain good repeatability of K_3 values. It was not enough to just backwash the filter between runs; the filter had to be disassembled and cleaned by hand. After this was done and the filter was reassembled, the precoating operation was as follows:

Water was pumped through the filter components for a few minutes to remove traces of air and diatomite.

Precoat diatomite (in slurry form) was put in the precoat pot and the magnetic stirrer was turned on to keep diatomite in suspension.

The recycle tank was filled and flow was cycled at the precoating flow rate as follows (figure 9): recycle tank→pump→bypass→filter→recycle tank, etc.

Flow was diverted through precoat pot and the bypass closed. Water was cycled in this manner until all diatomite was flushed from precoat pot onto septum (about 10 min).

Then the valves were adjusted to give the following flow pattern (figure 9): supply tank→pump→bypass→filter→flow meter→ to waste.

After completion of the above steps, precoating is complete, and the system is ready for the filtering operation. The trickiest part of the precoating operation is adjusting the flow rate for precoating. The flow rate has to be estimated from the appearance of the stream entering the recyle tank. If the estimate is a good one, a uniform precoat is formed (figure 10) and the run can proceed. A poor estimate, however, results in a precoat that must be discarded.

Since the septum of the EK filter lies in a vertical plane, the flow must be maintained through the septum to prevent the precoat from dropping from the septum (figure 11). During the filtering operation, the flow is adjusted successively to rates of approximately 2.5, 1.9, and 1.2 gpm/ft^2, and each flow rate and corresponding head loss are recorded. At the end of the filtering operation , the flow is stopped and the precoat is allowed to drop. The diatomite is then flushed out of the filter through the Tygon tubing on the front of the filter (figures 10, 11).

A typical K_3 data sheet (Data Sheet 2) is included in Appendix C. The K_3 value is determined from a plot of head loss vs. flow rate that is plotted on the data sheet.

TEST RESULTS

COMPOSITE CORRECTION

Composite correction curves were determined experimentally during this study for the two ASTM methods (figures 12, 13). The ordinate of each point of the plot is the negative of a hydrometer reading for the sedimentation suspension (appropriate quantity of dispersing solution and enough distilled water to bring total volume to 1000 ml) at the corresponding temperature. The largest difference in hydrometer readings (figure 13) is about 0.8 of a unit of the hydrometer scale. This difference in hydrometer readings for the same solution at the same temperature indicates that the actual reading of the hydrometer would be a major limitation to the repeatability of test results. Nevertheless, the repeatability of particle size test results was found to be excellent. The composite correction method of correcting hydrometer readings was used throughout the study because its use simplifies the calculations.

SERIES I

The ASTM D422-61T method used in determining the particle size distribution of C535/A when using 50, 30, and 20 gm samples respectively was repeatable (figures 14, 15, 16). ASTM D422-39 method when using 20 gm samples of C535/A also was repeatable (figure 17). All of the points plotted lie close to the "average" curves drawn through the points, and many of the points fall directly on top of previous points. Since the dispersing solution used in the ASTM D422-61T method was more easily and quickly prepared, and the repeatability of the two methods seemed to be equally good, it became obvious that this method was to be preferred.

The particle size distribution of C535/A determined by the D422-39 method was coarser than the corresponding particle size distribution determined by the D422-61T method when using 20 gm samples (figure 18). This difference in particle size between the two methods is probably due to the proportionately greater quantity of dispersing agent used in the D422-61T method (20 ml sodium silicate solution used in D422-39 and 125 ml sodium hexametaphosphate solution used in D422-61T). The sodium hexametaphosphate solution apparently is more effective in keeping the discrete particles separated, and there-

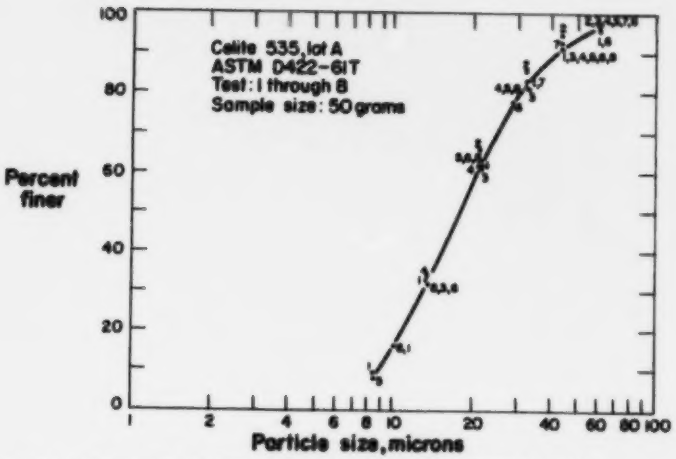


Figure 14. Repeatability of the ASTM D422-61T method using 50 gm samples of C535/A.

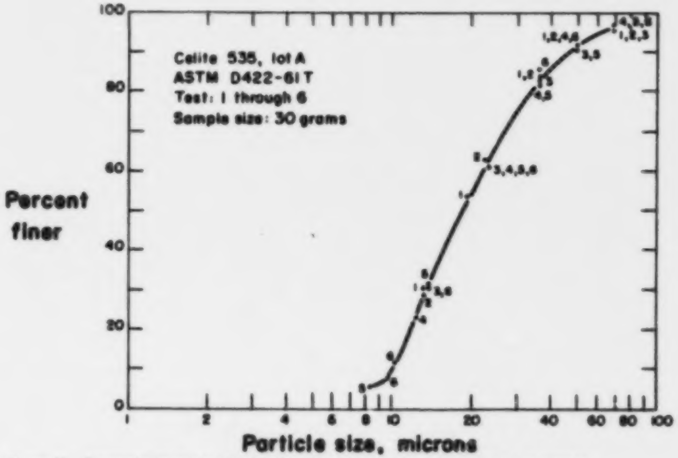


Figure 15. Repeatability of the ASTM D422-61T method using 30 gm samples of C535/A.

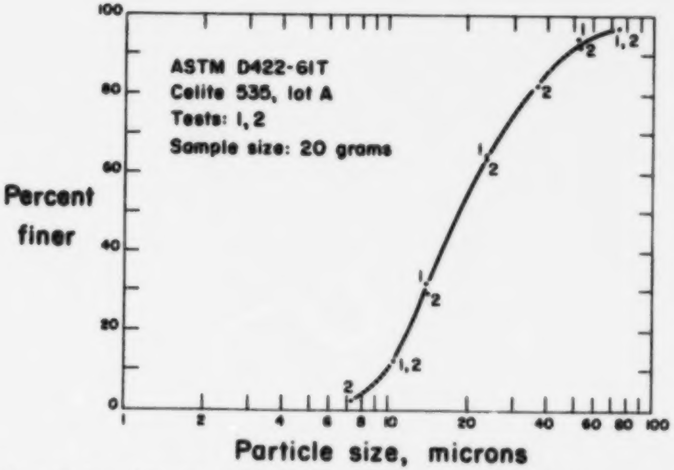


Figure 16. Repeatability of the ASTM D422-61T method using 20 gm samples of C535/A.

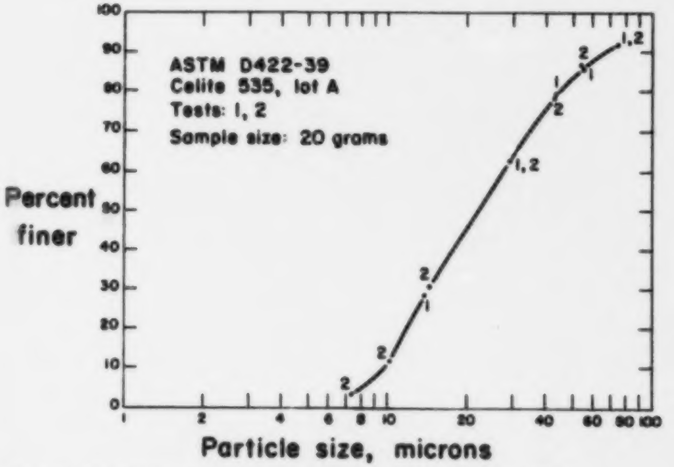


Figure 17. Repeatability of the ASTM D422-39 method using 20 gm samples of C535/A.

fore, is the more effective dispersing solution. For particle sizes less than 15µ, the curves in Figure 18 are almost the same. This is probably due to proportionately greater adsorption of the dispersing agents on the small particles because of their large surface area per unit weight. Because of the differences in the two methods, it was realized that they could not be used interchangeably. The sodium hexametaphosphate solution was easier to prepare, and for this reason, most subsequent particle size distributions were determined by the D422-61T method. The two methods were compared further using 30 gm samples.

The published ASTM D422-61T procedure specifies the use of samples of approximately 50 gm of soil when the soil is mostly of the clay and silt sizes covered by 125 ml of dispersing solution and then soaked for 18 hr. However, when 50 gm of C535/A was covered by 125 ml of dispersing solution, the filter aid adsorbed the solution "like a sponge", and some additional water had to be added to the mixture to soak the sample. This development illustrates the relatively higher porosity and surface area of diatomite over most engineering soils. It became apparent that it might be more desirable to use a diatomite sample size less than 50 gm. For this reason, particle size distributions were determined by the D422-61T method using 50, 30, and 20 gm samples of C535/A. The repeatability of the method seemed to be equally good for all three samples sizes (figure 14, 15, 16).

Figure 19 illustrates the effect of sample size on the particle size distribution of C535/A using the D422-61T method. The particle size results using 20 and 30 gm samples are almost identical. However, the results using 50 gm samples indicate a finer particle size distribution than the 20 and 30 gm results. The difference in particle size results between the 50 gm samples and the 30 and 20 gm samples was believed to have two causes that were probably significant when using 50 gm samples and less significant when using 30 or 20 gm samples, degradation of particle size during air dispersion, and hindered settling. It seems logical that there would be more degradation and hindered settling with 50 gm samples due to the increased probability of particle collision. A sample size of 30 gm was therefore chosen and used in subsequent particle size tests.

SERIES II

The four particle size tests that were run on each diatomite sample in Series II were plotted together. An average curve was drawn through the points of the three D422-61T tests, and the best curve was drawn through the points of the D422-39 test. The Series II particle size distribution curves presented are typical of all of the particle size distribution curves of the Series II tests.

The D422-61T method gave excellent repeatability of test results (figures 20, 21, 22, 23). Four of 19 such curves that establish the repeatability of the D422-61T method for determining the particle size distribution of diatomite filter aids when using sample sizes of 30 gm are given. Since the D422-61T method is also relatively simple and inexpensive to perform, it is suitable for use in a diatomite filter aid specification.

The D422-39 method gives coarser particle size results than the D422-61T method (figures 24, 25, 26, 27). These four curves are typical of 19 such curves all of which show that the D422-39 results

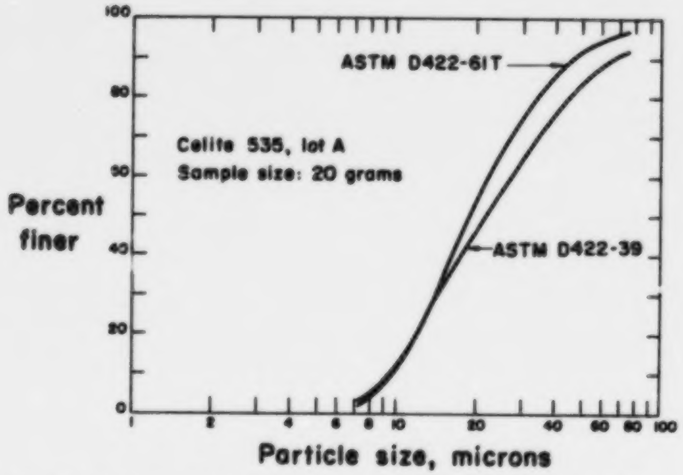


Figure 18. Comparison of particle size distributions determined by ASTM methods D422-39 and D422-61T using 20 gm samples of C535/A.

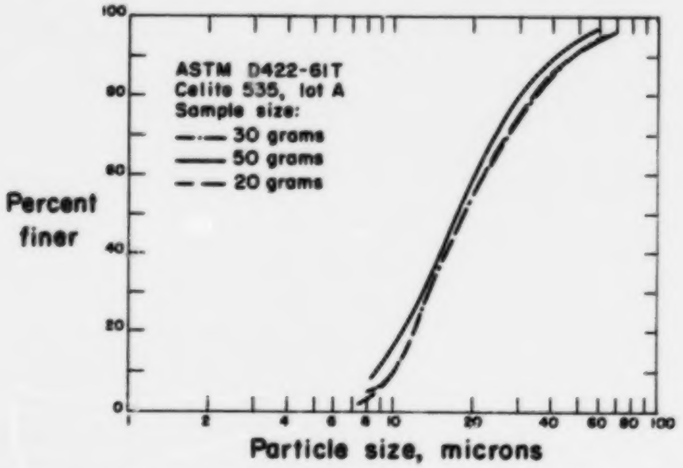


Figure 19. Effect of sample size on the particle size distribution of C535/A using ASTM method D422-61T.

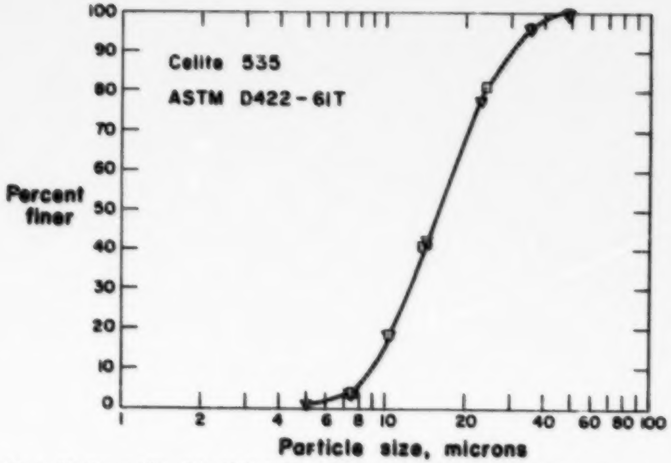


Figure 20. Repeatability of the ASTM D422-61T method in determining particle size distribution of C535/B (curve represents average of three tests).

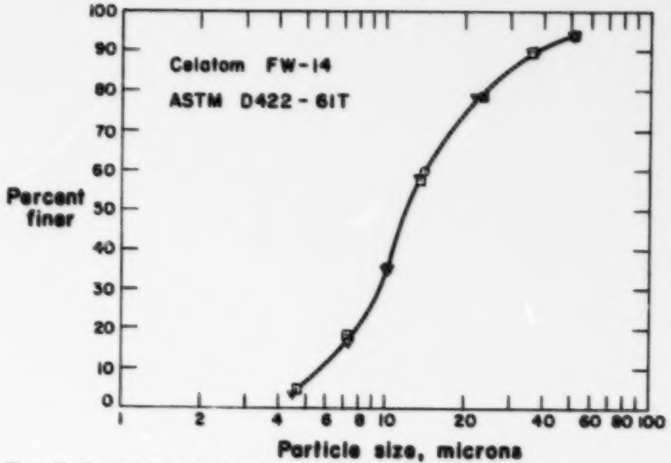


Figure 21. Repeatability of the ASTM D422-61T method in determining particle size distribution of FW-14 (curve represents average of three tests).

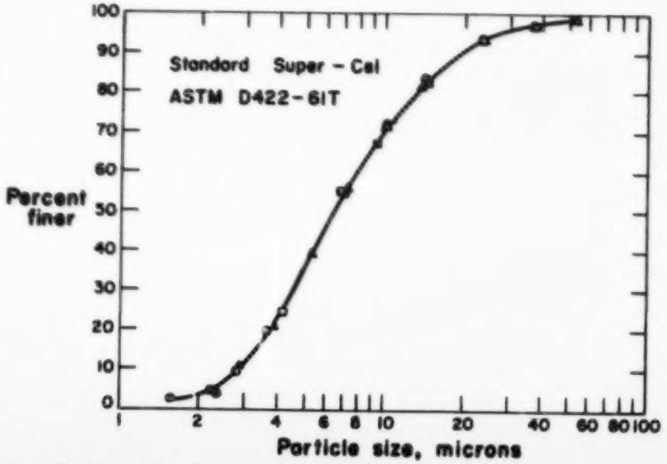


Figure 22. Repeatability of the ASTM D422-61T method in determining particle size distribution of Standard Super-Cel (curve represents average of three tests).

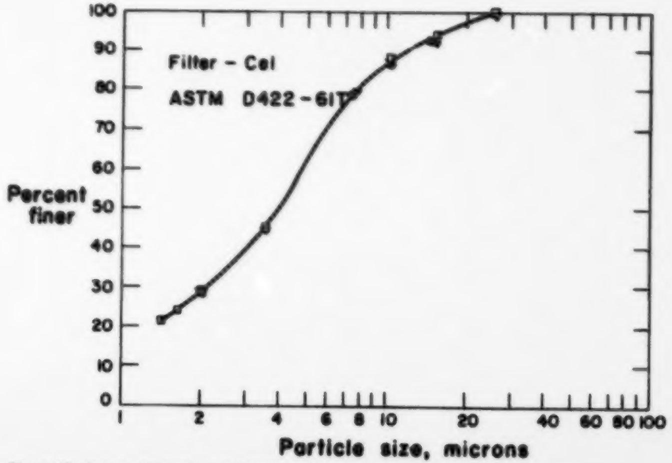


Figure 23. Repeatability of the ASTM D422-61T method in determining particle size distribution of Filter-Cel (curve represents average of three tests).

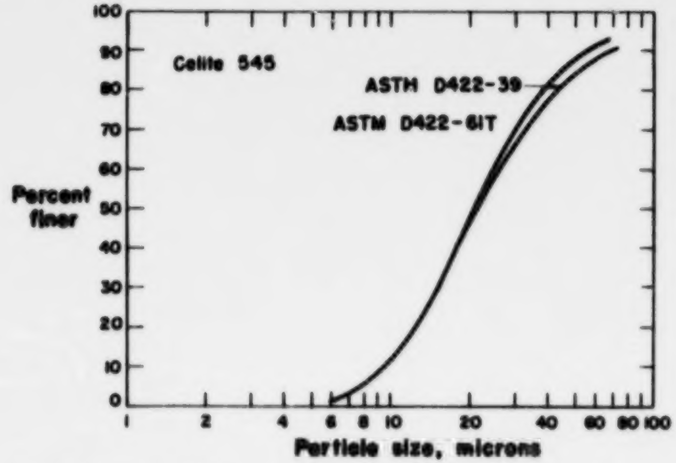


Figure 24. Comparison of the two methods, ASTM D422-39 and D422-61T, in determining the particle size distribution of C545.

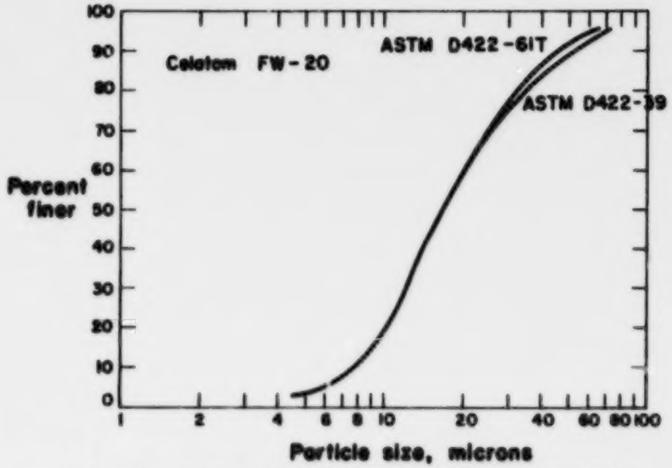


Figure 25. Comparison of the two methods, ASTM D422-39 and D422-61T, in determining the particle size distribution of FW-20.

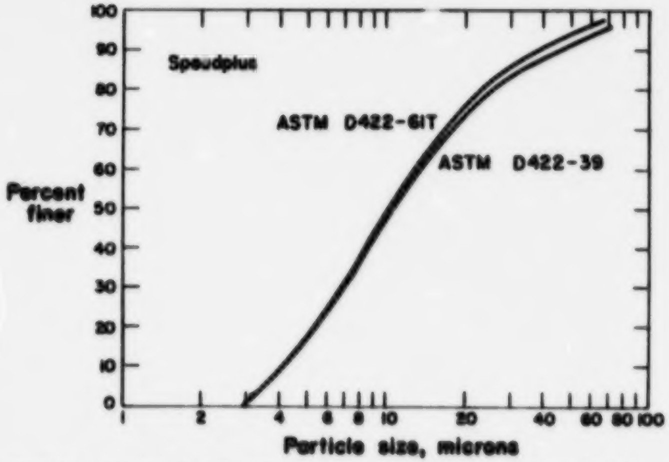


Figure 26. Comparison of the two methods, ASTM D422-39 and D422-61T, in determining the particle size distribution of Speedplus.

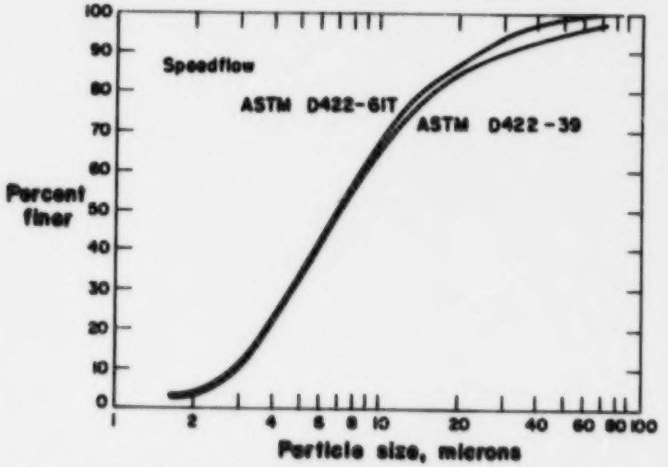


Figure 27. Comparison of the two methods, ASTM D422-39 and D422-61T, in determining the particle size distribution of Speedflow.

were coarser than the corresponding D422-61T results. However, the difference in the results between the two methods is not as great for 30 gm samples as it is for the 20 gm samples. Although the difference in particle size results between the two methods is not great, the two tests must not be used interchangeably. The D422-61T method is preferred because of the simpler preparation of the dispersing solution.

The filter aid samples tested in the Series II tests were supplied by the manufacturer as representative of their respective filter aid grades (figures 28, 29, and 30). The curves presented are the average curves for the three D422-61T tests.

The C535 curve shown in figure 28 is the particle size distribution of C535/B. The other lots of C535 have coarser particle size distributions than lot B, as will be demonstrated by the Series III results. The D4200 curve shown in figure 29 is the particle size distribution of D4200/A, which is finer than the other lot of D4200 (D4200/B) tested in Series III. The D4200 and D5000 curves are almost the same (figure 29). In fact, the particle size distribution of D4200/B determined in Series III is actually coarser than the D5000 curve (D4200 is normally finer than D5000). The curve for FW-50 was determined in the Series III tests, not in the Series II tests (figure 30). No FW-50 grade was available in the laboratory when the Series II tests were made. The FW-50 curve represents an average curve determined from the particle size results of the four lots of FW-50 from the Series III tests. The FW-60 curve is the particle size distribution of FW-60/E (figure 30).

SERIES III

The Series III tests consisted of tests made with different lots of the same grades of filter aid. Some of the particle size distribution curves determined in Series I and II tests are included with curves determined in the Series III tests and will be referred to as Series III particle size results. The curves determined in the Series I and II tests that are included in the Series III results are C535/A from Series I, C535/B from Series II, D4200/A from Series II, and FW-60/E from Series II.

Figures 31 through 35 summarize the Series III particle size results. There is considerable difference between Curves A and B in figure 31, A being much coarser than B. In fact, C535/A is coarser than the C545 that was tested in Series II (C535 is normally finer than C545). C535/B was the most recently acquired lot of C535 tested in this study. There is not very much difference between the curves for Lots C and D (figure 31). In figure 32, there is from 10 to 20 percent difference in the particle size of Curves A and B for D4200 below the 50 percent finer line, B being the coarser of the two curves. Only two lots of D4200 were available for testing. There is practically no difference in particle size distribution for Lots A, B, C, and D of FW-60 (figure 33), but there is a big difference between Lot E and the other four lots. Lots A, B, C, and D were received from the manufacturer in January, 1963, and Lot E was received from the manufacturer about four months earlier. Apparently, either the durations of time between the sampling of Lots A, B, C, and D were not long enough to allow normal variation in the particle size distribution, or the manufacturer desired to alter the particle size characteristics of FW-60. The particle size distributions

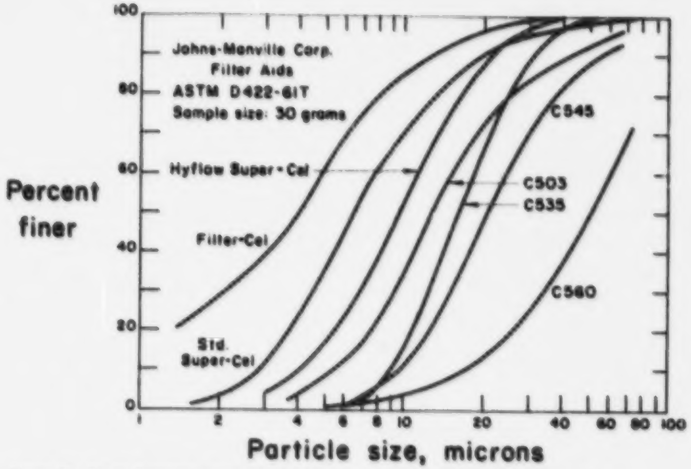


Figure 28. Series II particle size distributions for commercial filter aid grades supplied by Johns-Manville.

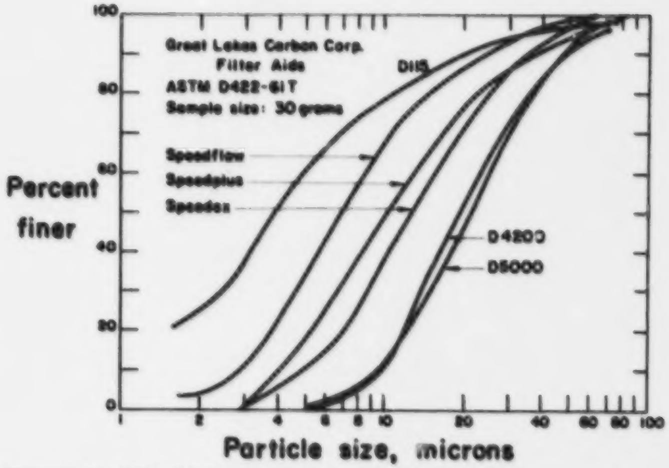


Figure 29. Series II particle size distributions for commercial filter aid grades supplied by Great Lakes Carbon.

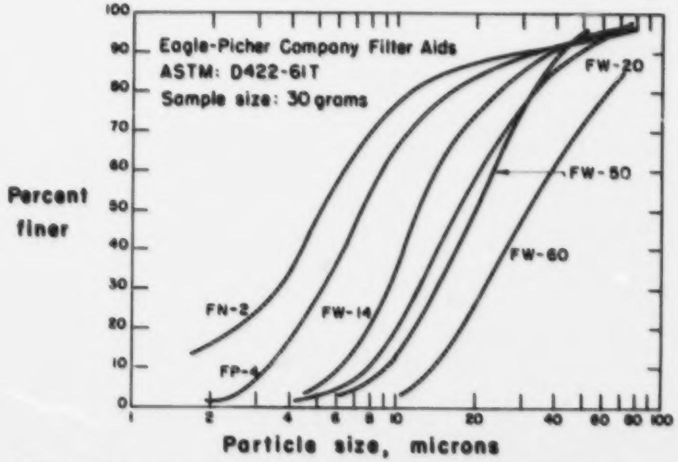


Figure 30. Series II particle size distributions for commercial filter aid grades supplied by Eagle-Picher.

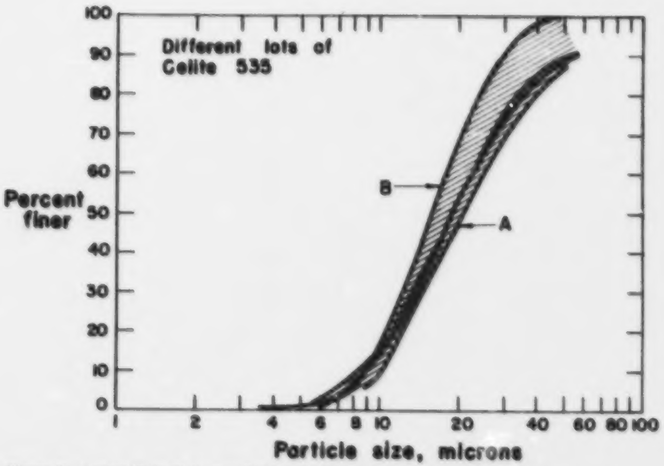


Figure 31. Series III particle size distributions for lots A, B, C, and D of C535. The two interior curves are C and D.

for the different lots of FW-50 and FW-20 are practically the same (figures 34, 35).

PERMEABILITY: K_3

All K_3 runs made before the precoat pot was added to the system were discarded because of their unreliability, probably due to particle size degradation. The results for K_3 of C535/B determined before the addition of the precoat pot averaged about 1.4 compared to the K_3 value of 1.00 determined after the addition. This indicates that an increase in K_3 of about 40 percent was realized when the precoat diatomite passed through the small pump.

After addition of the precoat pot, the K_3 runs were numbered from 1 to 143 in the order in which they were performed. The first 66 runs were also discarded because the apparatus was not disassembled and cleaned prior to each run. It was found that the repeatability of K_3 increased considerably when the apparatus was cleaned thoroughly between runs. Apparently, the adequacy of the backwashing method used was not sufficient when determining K_3. Also, the EK filter was being used simultaneously by another investigator to study the effects of solutions of salt and polyelectrolytes on streaming potential and zeta potential. It was found that when two supply tanks (one exclusively for K_3 and the other for streaming potential) were used and the apparatus was thoroughly cleaned to remove any residual chemical or polyelectrolyte from the system, the K_3 results were much better in repeatability. Apparently, small quantities of polyelectrolyte or salt affects the value of K_3. The few runs that were made after streaming potential runs and before it was realized that residual quantities of polyelectrolyte had to be cleaned from the system to obtain repeatable K_3 results, indicate that K_3 is slightly increased by minute quantities of polyelectrolyte. Further study is necessary, however, to verify this conclusion.

The K_3 results for runs 67 through 143 are tabulated (table II). Runs 77,78, 82, 83, 90, 92, and 93 (enclosed in parentheses in table III) were considered unreliable for the reasons noted in table II. When these seven runs were disregarded, the repeatability of K_3 results was good (table III). The K_3 values for these seven runs were ignored in the calculations of the average K_3 values (table III).

A summary of the K_3 values corresponding to the particle size distributions of Series II (figures 28, 29, and 30) and Series III (figures 31, 32, 33, 34, and 35) are shown in tables IV and V. The filter aid grades of each manufacturer are listed from coarsest at the top to finest at the bottom according to the manufacturers' ratings (table IV). As was expected, the K_3 values agree substantially with the manufacturers' ratings of filter aid grades; the K_3 increases for each step down the list.

Variation in K_3 is to be expected with different lots of the same filter aid (table V). The K_3 values indicate that there was considerable variation between lots of the same grade for some of the grades tested. The ratios of largest K_3 to smallest K_3 for each of the grades tested in Series III were: C535/B to 535/A, 1.82; D4200/A to D4200/B, 1.25; FW-60/B to FW-60/E, 1.65; FW-50/B to FW-50/D, 1.06; FW-20/A to FW-20/B, 1.08. These values demonstrate the necessity for standard filter aid specifications, and also the necessity for determining particle size and permeability of filter aids used in research. These results indicate that variation in filter aid characteristics from one shipment to the next may

TABLE II. K_3 RESULTS FOR DIATOMITE SAMPLES LISTED IN TABLE I (K_3 at 20°C)

Run	Sample	K_3	Run	Sample	K_3
67	C535/C	0.91			
68	C535/B	1.00	106	FW-50/A	1.00
69	C535/B	1.00	107	FW-50/B	1.00
70	C535/B	1.00	108	FW-50/B	1.01
71	C535/A	0.53	109	FW-50/B	0.99
72	C535/A	0.54	110	FW-50/C	0.92
73	C535/B	1.00	111	FW-50/C	0.96
74	C535/A	0.58	112	FW-50/C	0.97
75	C535/A	0.56	113	FW-50/D	0.95
76	C535/A	0.55	114	FW-50/D	0.93
77	C535/C	0.82[a]	115	FW-50/D	0.93
78	C535/C	0.83[a]	116	FW-60/A	0.71
79	C535/C	0.96	117	FW-60/A	0.74
80	C535/C	0.90	118	FW-60/B	0.75
81	C535/C	0.94	119	FW-60/B	0.77
82	C535/C	0.98[b]	120	FW-60/C	0.72
83	C535/C	0.75[c]	121	FW-60/C	0.73
84	C535/C	0.89	122	FW-60/D	0.76
85	C535/D	0.66	123	FW-60/D	0.77
86	C535/D	0.65	124	FW-60/E	0.46
87	C535/C	0.91	125	FW-60/E	0.47
88	C535/D	0.68	126	FW-20/A	1.71
89	C535/D	0.65	127	FW-20/A	1.62
90	C535/A	0.49[c]	128	FW-20/B	1.51
91	C535/A	0.57	129	FW-20/B	1.57
92	C535/B	0.90[d]	130	FW-20/C	1.51
93	C535/B	0.93[a]	131	FW-20/C	1.57
94	C535/B	0.99	132	FW-20/D	1.56
95	C535/C	0.92	133	FW-20/D	1.54
96	C535/D	0.67	134	FW-20	1.39
97	D4200/A	0.84	135	C560	0.24
98	D4200/A	0.84	136	C545	0.70
99	D4200/A	0.85	137	C545	0.75
100	D4200/A	0.85	138	FW-14	2.96
101	D4200/B	0.66	139	D5000	0.68
102	D4200/B	0.67	140	C503	2.08
103	D4200/B	0.69	141	Hyflo Super-Cel	3.57
104	FW-50/A	0.94	142	Speedplus	3.83
105	FW-50/A	1.00	143	Speedex	2.55

---

[a] A good precoat was not formed.

[b] The septum was not well cleaned prior to run.

[c] A poor precoat was formed.

[d] The precoat pot was not well cleaned prior to run.

TABLE III. REPEATABILITY OF K_3 RESULTS (K_3 at 20°C)

Sample	Run	K_3
C535/C	67	0.91
	77	(0.82)
	78	(0.83)
	79	0.96
	80	0.90
	81	0.94
	82	(0.98)
	83	(0.75)
	84	0.89
	87	0.91
	95	0.92
	Average	0.92
C535/D	85	0.66
	86	0.65
	88	0.68
	89	0.65
	96	0.67
	Average	0.66
D4200/B	101	0.66
	102	0.67
	103	0.69
	Average	0.67
FW-50/A	104	0.94
	105	1.00
	106	1.00
	Average	0.98
FW-50/C	110	0.92
	111	0.96
	112	0.97
	Average	0.95
FW-60/A	116	0.71
	117	0.74
	Average	0.72
FW-60/C	120	0.72
	121	0.73
	Average	0.72
FW-60/E	124	0.46
	125	0.47
	Average	0.46
FW-20/B	128	1.51
	129	1.57
	Average	1.54
FW-20/D	132	1.56
	133	1.54
	Average	1.55
C535/B	68	1.00
	69	1.00
	70	1.00
	73	1.00
	92	(0.90)
	93	(0.93)
	94	0.99
	Average	1.00
C535/A	71	0.53
	72	0.54
	74	0.58
	75	0.56
	76	0.55
	90	(0.49)
	91	0.57
	Average	0.55
D4200/A	97	0.84
	98	0.84
	99	0.82
	100	0.85
	Average	0.84
FW-50/B	107	1.00
	108	1.01
	109	0.99
	Average	1.00
FW-50/D	113	0.95
	114	0.93
	115	0.93
	Average	0.94
FW-60/B	118	0.75
	119	0.77
	Average	0.76
FW-60/D	122	0.76
	123	0.77
	Average	0.76
FW-20/A	126	1.71
	127	1.62
	Average	1.66
FW-20/C	130	1.51
	131	1.57
	Average	1.54

account for an 80 percent change in research results.

A filter aid sample may sometimes be coarser than one of a different grade that is normally coarser (tables IV, V). C545 is normally coarser than C535, but both C535/A and C535/D (table V) have smaller K_3 values than C545 (table IV), indicating that these two lots of C535 are coarser than C545. D5000 is normally coarser than D4200, but the K_3 values for D5000 (table IV) and D4200/B (table III) are practically the same. This further illustrates the need for a standard diatomite filter aid specification.

Attempts were made to determine K_3 values for Speedflow, Standard Super-Cel, and FP-4, but they were too fine to be measured with the EK filter apparatus. The head losses that developed across the precoats were much too high to measure with the manometer used. No attempt was made to determine K_3 values for D115, Filter-Cel and FN-2, because they are finer than the above three grades. None of these six grades of filter aid are ordinarily used in water filtration practice.

INTERPRETATION OF TEST RESULTS

The methods used in this study to determine particle size distribution and K_3 values would be suitable for use in diatomite specifications. But to set the limits of K_3 and particle size to be specified, the limits desirable for particular applications and the limits that the manufacturer can be expected to meet must be determined. This will involve an evaluation of the effects of filter aid particle size and K_3 on the value of K_4 in equation 1.

The specification of particle size distribution of diatomite could be set forth by stating the limits of variation of particle size, corresponding to any given value of percent finer, to a range of the specified particle size ± 10%. Another method of specifying particle size distribution is to specify limits of weight percent of the filter aid within each of several ranges of particle size— e.g., 0 - 1% (by weight) less than 2μ, 3 - 5% between 2 and 6μ, 10 - 16% between 6 and 10μ, etc. Before either type of specification can be written, the desired particle size distribution and the allowable limits of variation for a particular application need to be determined. Specification of permeability could be accomplished by simply limiting the variation of K_3 to a range of the specified K_3 value ± 10%.

COMPARISON OF K_3 WITH MEAN PARTICLE SIZE

The comparison of K_3 with mean particle size (the particle size corresponding to the 50 percent finer line on the particle size distribution curve) for Series II and III are given (table IV, V). The attempt to correlate K_3 and mean particle size (mps) had little success. The K_3 values are not consistent with the mps values. The value of K_3 should decrease when mps increases, other things being equal. Several inconsistencies of K_3 and mps are apparent (table VI). The K_3 values of C545 and C535/A are 0.73 and 0.55 respectively, but both have an mps of 21.0μ. The K_3's of C535/B and FW-20/C are 1.00 and 1.54 respectively, but both have an mps of 16.2μ. Similarly, the K_3's of C535/C and C535/D are 0.91 and 0.67 respectively, but both have an mps of 18.8μ. Further, the K_3's of D4200/A and FW-50 are 0.84 and 0.97 respectively, but both have an mps of 19.3μ. The K_3's of both C535/D and D4200/B are 0.67, but their respective values of mps are 18.8 and 21.5. These and other inconsistencies with the K_3 and particle size results explain the poor success in correlating K_3 and mps.

Attempts were also made to correlate K_3 with several quantities calculated from the particle size distribution curve. One such quantity was:

$$P_{20} + 2P_{15} + 3P_{10} + 4P_8 + 5P_6$$

where: P_{20} = percent finer than 20μ
P_{15} = percent finer than 15μ etc.

This is similar to the way in which the fineness modulus of sand is calculated. Although this quantity seemed to charac-

TABLE IV. COMPARISON OF K_3 WITH MEAN PARTICLE SIZE FOR SERIES II (K_3 at 20°C)

Grade	K_3	Mean particle size (mps), μ
Johns-Manville Grades		
C560	0.24	50.0
C545	0.73	21.0
C535/B	1.00	16.2
C503	2.08	12.8
Hyflo Super-Cel	3.57	9.5
Standard Super-Cel		6.4
Filter Cel		4.0
Great Lakes Carbon Grades		
D5000	0.68	21.8
D4200/A	0.84	19.3
Speedex	2.55	13.0
Speedplus	3.83	10.4
Speedflow		7.0
D115		3.8
Eagle-Picher Grades		
FW-60/E	0.46	32.0
FW-50	0.97	19.3
FW-20	1.39	17.0
FW-14	2.96	12.0
FP-4		7.3
FN-2		5.1

TABLE V. COMPARISON OF K_3 WITH MEAN PARTICLE SIZE FOR SERIES III (K_3 at 20°C)

Grade	K_3	Mean particle size, μ
C535/A	0.55	21.0
C535/B	1.00	16.2
C535/C	0.92	18.8
C535/D	0.66	18.8
D4200/A	0.84	19.3
D4200/B	0.67	21.5
FW-60/A	0.72	22.0
FW-60/B	0.76	21.2
FW-60/C	0.72	22.0
FW-60/D	0.76	21.6
FW-60/E	0.46	32.0
FW-50/A	0.98	19.8
FW-50/B	1.00	18.0
FW-50/C	0.95	20.0
FW-50/D	0.94	19.4
FW-20/A	1.66	15.5
FW-20/B	1.54	14.4
FW-20/C	1.54	16.2
FW-20/D	1.55	14.9

TABLE VI. INCONSISTENCIES OF K_3 AND MEAN PARTICLE SIZE RESULTS (K_3 at 20°C)

Sample	K_3	mps, μ	From Table
FW-20/C	1.54	16.2	IV
FW-20/D	1.55	14.9	IV
C535/B	1.00	16.2	IV
FW-20/C	1.54	16.2	IV
C535/C	0.91	18.8	IV
C535/D	0.67	18.8	IV
C535/B	1.00	16.2	IV
FW-50/B	1.00	18.0	IV
FW-50/A	0.98	19.8	IV
D4200/A	0.84	19.3	IV
FW-50	0.97	19.3	III
C535/D	0.67	18.8	IV
D4200/B	0.67	21.5	IV
C545	0.73	21.0	III
C535/A	0.55	21.0	IV
C535/A	0.55	21.0	IV
FW-60/B	0.76	21.2	IV

TABLE VII. COMPARISON OF AVERAGE K_3 (avg K_3) AND MEAN PARTICLE SIZE (mps) RESULTS WITH THE TABLE OF FILTER AID RATINGS REPORTED BY EAGLE-PICHER CO.[8] (K_3 at 20°C)

Eagle-Picher	avg K_3	mps μ	Johns-Manville	avg K_3	mps μ	Dicalite	avg K_3	mps μ
			C560	0.24	50.0			
FW-60	0.68	23.8	C545	0.73	21.0	D5000	0.68	21.8
FW-50	0.97	19.3	C535	0.78	18.7	D4200	0.76	20.4
FW-20	1.57	15.2	C503	2.08	12.8	Speedex	2.55	13.0
FW-14	2.96	12.0	Hyflo Super-Cel	3.57	9.5	Speedplus	3.83	10.4
FP-4		7.3	Std. Super-Cel		6.4	Speedflow		7.0
FN-2		5.1	Filter-Cel		4.0	D115		3.8

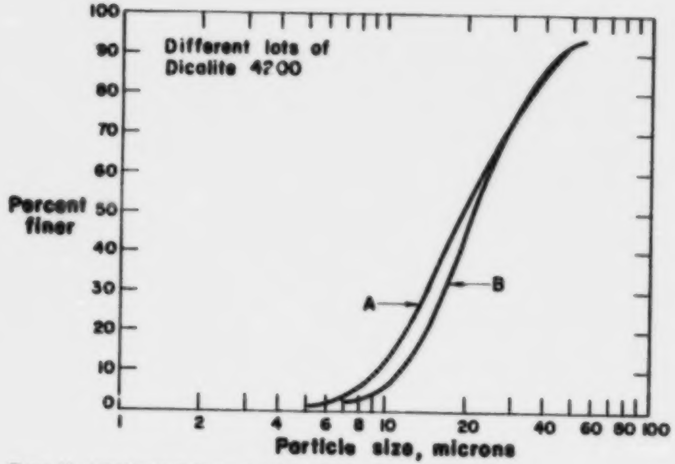


Figure 32. Series III particle size distributions for lots A and B of D4200.

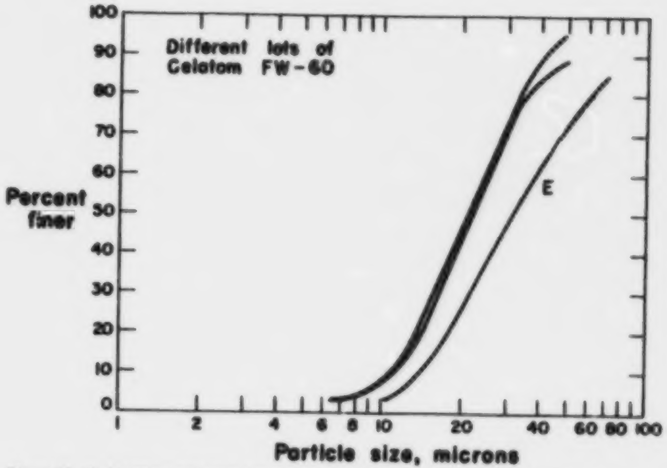


Figure 33. Series III particle size distributions for lots A, B, C, D, and E of FW-60. Curves A, B, C, and D were within the range of the two unlettered curves.

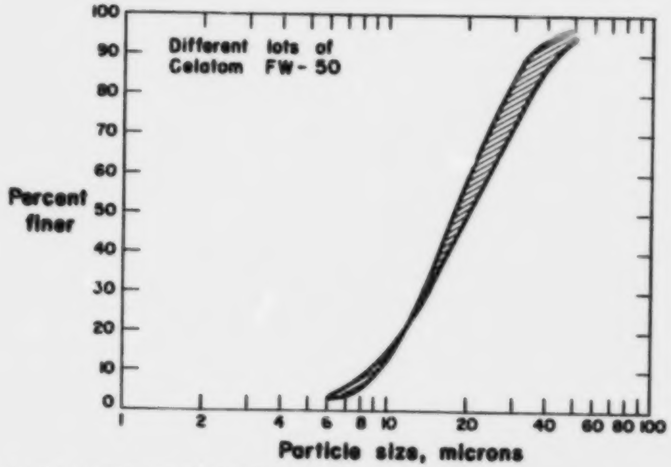


Figure 34. Particle size distributions for lots A, B, C, and D of FW-50. All four curves were within the range shown.

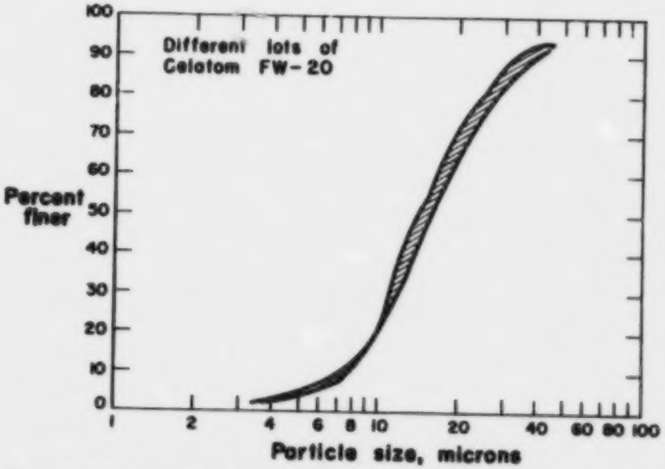


Figure 35. Particle size distributions for lots A, B, C, and D of FW-20. All four curves were within the range shown.

terize the particle size distribution curve better than mps, its correlation with K_3 was not a significant improvement over the correlation of mps and K_3. The poor correlation between K_3 and characteristics of particle size distribution indicates that K_3 does not depend on particle size distribution alone, but also depends on other variables. Other variables that K_3 might depend on are the location of the source of the diatomite, how the diatomite is processed, the shape of the diatomite particles, the types of diatom fossils in the diatomite, and others. Additional questions need to be answered. How are the filtering characteristics of a diatomite filter aid affected by these other variables? How is K_4 affected by these other variables? Is K_4 more dependent on particle size distribution than it is on K_3, or vice versa? Would a diatomite filter aid specification that includes specifications for type of filter aid, particle size distribution, K_3, and surface charge be adequate, or would a specification of K_4 as determined by filtering a standard, synthetic water under standard conditions have to be included? Further research is needed to find the answers to these questions.

COMPARISON OF RESULTS WITH OTHER WORK

Two particle size distribution curves of C545, one determined in this study by the D422-61T method and one reported earlier[10] are shown (figure 36). There is considerable difference in the two curves, the JM curve being the coarser. But the manufacturer does not normally use the D422-61T method for determining particle size distributions of his filter aids. Since the same method was not used to determine both curves, the actual difference in the particle size distributions of the two lots of C545 corresponding to the two curves cannot be effectively evaluated. Figure 37 shows two particle size distribution curves for C503 determined in this study and one curve for C503 determined by the manufacturer. The differences between the curves of figure 37 are not as great as the difference between the two curves of figure 36. Figure 37 cannot be used to evaluate the actual difference in the particle size distributions of the two lots because the same method was not used to evaluate the curves.

Figure 38 shows how the particle size distribution of C535 reported earlier compares with the range of particle size distributions for the four lots of C535 tested in this study by the D422-61T method[3]. The method used to determine particle size distribution was practically the same as the D422-61T method used in this study. Therefore, most of the differences between curve X and the lots of C535 tested in this study can probably be attributed to an actual difference in particle size distribution. For particle sizes greater than 12μ, curve X corresponds closely to the curve for C535/A; but below 12μ, the curve is shifted slightly upwards, indicating that X was finer than C535/A. It is therefore estimated that curve X would correspond to a K_3 value somewhat greater than 0.55, the K_3 of C535/A. The K_3 for X was probably about 0.70.

The filter aids in table VII are listed from coarsest at the top to finest at the bottom in accordance with the table of filter aid ratings reported by the supplier[8]. The listing illustrates how the filter aids of the three suppliers are expected to compare. Average K_3 and mps results are included in table VII for comparison. The results of this study agreed, for the most part, with the reported filter aid ratings. However, there is quite a difference in the K_3 and particle size results of this study for any given line of table VII. The K_3 values of

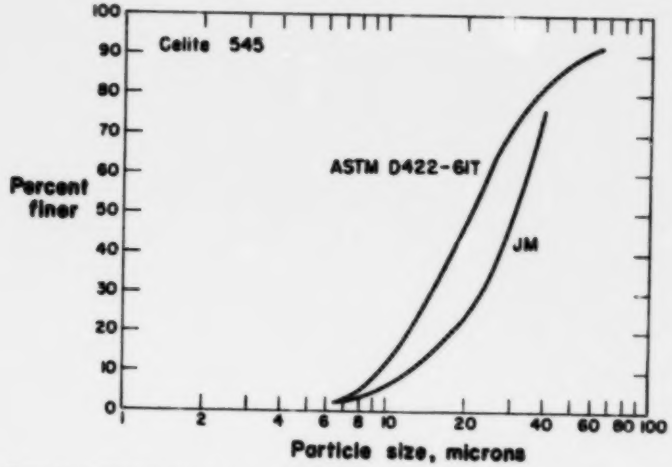


Figure 36. Comparison of particle size distributions for C545. The curve labeled ASTM D422-61T is part of the Series II results of this study. The curve labeled JM was taken from a Johns-Manville brochure (10).

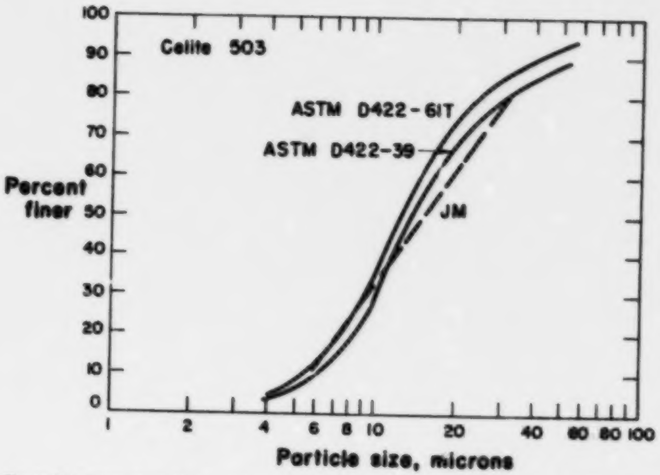


Figure 37. Comparison of particle size distributions for C503. The curves with the ASTM labels are part of the Series II results of this study. The curve labeled JM was taken from a Johns-Manville brochure (10).

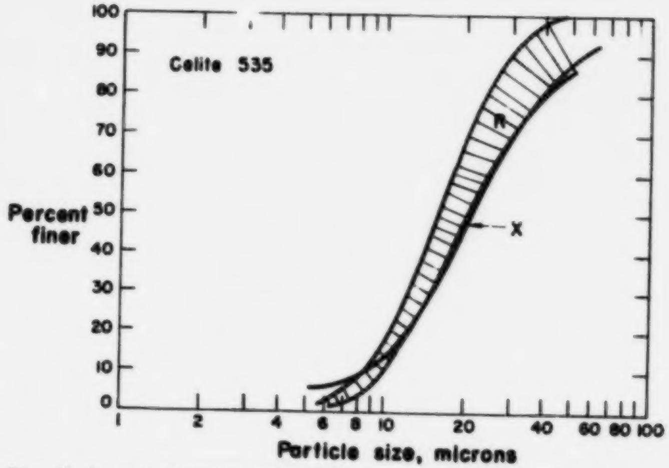


Figure 38. Comparison of particle size distributions for C535. The range labeled R is the range of the Series III results. The curve labeled X was reported by Baumann in 1950 (3).

C545, C535, D5000, and D4200 do not show much difference (table VII), indicating that the flow characteristics of these four grades were not much different when they were tested in this study.

SUMMARY AND CONCLUSIONS

Filter aid specifications for the hydraulic characteristics of filter aids become more important as the use of diatomite filtration for the production of potable water increases. Filter aid specifications should include standardized methods for determining the hydraulic characteristics of the filter aid. A standard method must be relatively inexpensive and simple to perform and must give consistent, reproducible results.

Two modified ASTM methods for determining particle size and a method for determining a characteristic of permeability (K_3) by use of a small pressure filter (EK filter) were investigated in this study for possible use in filter aid specifications. The results indicate that the ASTM D422-61T method of particle size analysis, as used in this study, and the procedure used to determine K_3 values with the EK filter meet these requirements and would, therefore, be suitable for use in filter aid specifications.

Particle size distributions were determined for each of the samples of 19 commercial grades of filter aids listed (table I). K_3 values were determined for each of the 19 filter aid grades except Speedflow, Standard Super-Cel, FP-4, D115, Filter-Cel, and FN-2. K_3 values for these six grades could not be measured with the EK filter apparatus without further modification because of their high head-loss characteristics.

The following conclusions were drawn from this investigation:

The ASTM methods, D422-39 and D422-61T are equally repeatable. The D422-61T test was used for most of the particle size tests made in this study because the dispersing agent was easier to prepare.

The composite correction method for correcting hydrometer readings simplifies the test procedure and is adequate when temperature variations are small.

The particle size results obtained when using 50 gm samples are slightly finer than corresponding results obtained when using either 30 or 20 gm samples. This is probably due to greater particle size degradation from the air dispersion tube and more hindered settling in the smaller samples. There is more chance for particle collision when using 50 gm samples.

More effective particle dispersion is realized in the D422-61T test. The most effective dispersion probably results from the greater quantity of dispersing agent used in the D422-61T test.

The D422-61T test, as modified in this study for application to diatomite filter aids, gives consistent, repeatable results.

The assumption that the head loss through the septum is negligible was found to be valid up to a flow rate of at least 2.55 gpm/ft^2 for the septum of stainless steel mesh used in the EK filter.

K_3 results obtained with the EK filter are repeatable when precautions are taken to insure clean apparatus. With the proposed revisions of apparatus repeatability should improve.

Minerals, including polyelectrolytes, in the water being filtered may affect the K_3 value of the filter aid. It was found that the system had to be cleaned thoroughly to obtain repeatable K_3 results.

The significant decrease in K_3 results after the precoat pot was added indicates that diatomite filter aid particles are degraded when they pass through a pump. Other types of equipment such as feeders, mixers, and ejecters may also degrade filter aid particles.

K_3 depends not only on the particle size distribution of the filter aid but also, to a lesser extent, on other characteristics of the filter aid.

There have been and may continue to be variations in the hydraulic characteristics of a given commercial grade of filter aid between different shipments. This variation in some may result in the overlapping of the hydraulic characteristics of two normally different grades of filter aid.

RECOMMENDATIONS

The following are the recommendations as results of this investigation:

1. The needle valve of the EK filter apparatus should be replaced by a more effective and more easily operated flow controller.
2. The flow meter should be replaced by a flow meter capable of measuring higher flow rates with at least the same degree of accuracy.
3. A large manometer capable of measuring a greater range of head loss should replace the present manometer.
4. The flow pattern of the apparatus should be revised to allow backwashing by reverse flow.
5. Until a better method is developed, the ASTM D422-61T method should be used as the standard method for determining the particle size distributions of diatomite filter aids.
6. For application to diatomite filter aids, the D422-61T method should be performed using 30 gm samples, an air dispersion tube operated at 5 psi for 5 min, a constant temperature water bath or a constant temperature room, the composite correction method for correcting hydrometer readings, and the exact amount of dispersing agent prescribed by ASTM[1].
7. Until a better method is developed, K_3 should be determined with a filter apparatus similar to the EK filter apparatus when it is used to specify the permeability of diatomite filter aids.
8. When determining K_3, precautions should be taken to insure that the apparatus is clean if reliable values of K_3 are to be obtained.
9. Engineers and researchers should be aware of the possibility of particle size degradation of diatomite filter aids by pumping, feeding, mixing, and other operations.
10. The K_3 and particle size distribution of each shipment of filter aid received should be determined routinely.
11. More work should be done in this area in order to determine:
    a. The effects of chemicals, including polyelectrolytes, on the values of K_3 and K_4;
    b. The ranges of particle sizes and K_3 to be expected from the manufacturers;
    c. The ranges of particle sizes and K_3 desirable for applications to different types of raw water (surface water supply, ground water supply, etc.);
    d. The effects of K_3 and particle size on K_4; and
    e. The particle size degradation to be expected from different types of equipment.

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APPENDIX A. DEFINITION OF TERMS

Body feed

During the filtering cycle, diatomite filter aid is added proportionately to the raw water entering the filter. This added filter aid is the body feed. The mixture of body feed and suspended impurities is filtered out of the water during filtration and forms a porous cake on the precoat.

Body feed layer

The body feed layer is the porous cake that forms on the precoat when the mixture of body feed and suspended impurities is filtered out.

Colloid

Colloids make up the class of particles with special properties because of the extremely small size of the particles. The size of colloids is around 1μ and less, but larger than ordinary molecules (macromolecules are often included in this colloidal class).

Diatomite

Diatomite, diatomaceous earth, diatomaceous silica, and kieselguhr are synonymous terms for siliceous fossil remains of diatoms. Diatoms are microscopic plants that are capable of incorporating silica in their shells. Diatomite is well suited for use as filter aids because of its small particle size, low density (15#/ft^3), strength, high porosity (85-90%), and chemical inertness. In the production of diatomite filter aids, the crude diatomite is subjected to various processes such as drying, delumping, and various degrees of heat treatment. Diatomite filter aids are commonly referred to as diatomite.

Electrophoresis

Electrophoresis is the movement of charged particles through the liquid in which they are suspended when an electrical potential is applied across the liquid.

Filter aid

A filter aid is a material that is used to improve the filtration process. It does this by providing good impurities removal and a more porous filter cake. Without the continuous addition of filter aid (body feed) to the raw water, the impurities being removed from the water would quickly form a nonporous layer and clog the filter cake. When body feed is added continuously to the raw water, the body feed particles form a porous lattice structure that entrains the suspended impurities and prevents clogging and rapid buildup of head loss.

Filter cake

Depending on the context in which it is used, the term filter cake means either the precoat, when there is no body feed layer, or the precoat and body feed layer together, or the body feed layer when there is no precoat.

Hydrometer

An hydrometer is an instrument used for measuring the specific gravity of a liquid. It works on the basis of Archimedes' Principle— the weight of a floating object equals the weight of the liquid displaced. The specific gravity of a liquid is inversely proportional to the volume of liquid displaced by a given weight. The specific gravity is determined from the reading on the hydrometer stem at the meniscus of the liquid. This reading is related to the depth of the hydrometer bulb below the surface, and it therefore indicates the specific gravity of the liquid.

Permeability

The ability of a layer of porous material such as diatomite or soil to transmit a liquid under the influence of a pressure differential or hydraulic gradient is termed the permeability of the material. The term permeability is often used as a synonym for coefficient of permeability. The coefficient of permeability has the dimensional units of velocity (length/time) and is usually stated as a flow rate per unit area produced by an hydraulic gradient of unity.

Precoat

The initial layer of filter aid placed on the septum at the beginning of a run is called the precoat. It provides an extra barrier to bacteria and suspended solids and allows effective removal of suspended solids at the beginning of a run. It also prevents clogging of the septum.

Precoat pot

The precoat pot is a pressure container in which the precoat diatomite is placed at the beginning of a run. The flow is diverted through the precoat pot to flush the precoat diatomite into the flow in order to deposit it on the septum.

Septum

The septum is the filter element that serves as a support for the precoat. The precoat diatomite is filtered from the water by the septum, and thus, a thin layer of diatomite (precoat) is formed on the septum.

Terminal head loss

The terminal head loss is the head loss across the filter cake just before the filtering operation is terminated and the septum backwashed.

Turbidity

Turbidity is a measure of the ability of a sample of water to absorb light. It is a measure of the amount of suspended and colloidal material (dirt) in the water.

Zeta potential

When a colloidal particle is suspended in water, a thin liquid layer called the fixed layer surrounds the colloid and moves through the water with the colloid. The electrical potential difference between the outer edge of the fixed layer and a point of electroneutrality in the water is referred to as the electrokinetic or zeta potential.

APPENDIX B. ABBREVIATIONS

Abbreviation	Meaning
ASTM	American Society for Testing and Materials
avg	average
EK filter	electrokinetic filter
ft	feet
gal	gallons
gm	grams
gpm	gallons per minute
hr	hours
ID	inside diameter
in.	inches
min	minutes
ml	milliliters
mm	millimeters
mps	mean particle size
OD	outside diameter
ppm	parts per million
psi	pounds per square inch (gage)
sec	seconds
vs	versus
wt	weight
°C	degrees Centigrade

Abbreviation	**Meaning**	**Abbreviation**	**Meaning**
μ	microns (10^{-6} meters)	#	pounds

APPENDIX C. TYPICAL DATA SHEETS AND CALCULATIONS

PARTICLE SIZE DISTRIBUTION

The particle size distribution curve consists of a plot of the log of the particle size, Log D, plotted as abscissa, and the percent of the sample weight that is finer than the corresponding particle size, P, plotted as ordinate (column 7 versus log (column 5) of data sheet 1). D is related to the settling velocity by Stoke's law. In the calculations, the settling velocity, v_s, is taken as the effective depth of the hydrometer bulb below the surface of the liquid divided by the time of sedimentation ($v_s = L/T$). According to Stoke's law[1]:

$$D^2 = 30\, n\, v_s / 980\, (G - G_1) \quad . . . . . \quad (8)$$

where:
- D = particle size diameter (mm)
- n = coefficient of viscosity (poises) of the suspending medium, which is assumed to be water for practical purposes
- v_s = settling velocity (cm/min)
- G = specific gravity of the diatomite sample
- G_1 = specific gravity of the suspending medium - assumed to be 1.00 for practical purposes.

To convert the particle size diameter to microns (μ), equation 8, after replacing G_1 by 1, may be rewritten as:

$$D = \sqrt{30,610\, n v_s / (G-1)} \quad . . . . \quad (9)$$

where:
- D = particle size diameter (μ)
- n = viscosity of water (poises)
- v_s = settling velocity (cm/min)

So long as the temperature remains constant throughout the test, all terms on the right hand side of equation 9 remain constant except v_s, and equation 9 may be written in the shorter form:

$$D = \sqrt{\beta v_s} \quad . . . . \quad (10)$$

where $\beta = 30,610 n/(G-1)$ = a constant.

The percent finer, P, is related to the hydrometer reading. P at any time is equal to the weight of sample in suspension at that time, W_s, divided by the total oven dry weight of the sample, expressed as a percentage:

$$P = 100 W_s / WF \quad . . . . \quad (11)$$

where W = sample weight (gm)
F = hygroscopic moisture correction factor (oven dry wt/W). F was found to be 1.00 for all practical purposes.

The hydrometer used in this study was graduated to read in grams of soil (specific gravity = 2.65) in suspension in water at 20°C. In accordance with these considerations, the weight of diatomite in suspension is determined from:

$$W_s = R_c (2.65 - 1)\, G / 2.65\, (G-1)$$
$$= 0.622\, R_c G / (G-1)$$

in which R_c = corrected hydrometer reading, R + composite correction. Substitution into equation 11 yields:

$$P = 62.2\, R_c G / WF (G - 1) \quad . . . . . \quad (12)$$

So long as the temperature remains constant throughout the test, all terms on the right hand side of equation 12 remain constant except R_c, and equation 12 can be written in the shorter form:

$$P = \gamma R_c \quad . . . . \quad (13)$$

where $\gamma = 62.2\, G / WF(G-1)$ = a constant.

The specific gravity of each diatomite sample was determined by the pycnometer method used for soils. For Standard Super-Cel, G was found to be 2.14. The actual data taken and the calculations performed to determine the particle size distribution of Standard Super-Cel using ASTM D422-61T are illustrated in data sheet 1. In data sheet 1, columns 1 and 2 and the underlined material at the top of the data sheet were recorded either at the beginning of or during the test. The underlined initials near the top of the data sheet are the initials of the person who performed the test. Column 3 values are the effective depths of the hydrometer bulb below the surface of the liquid corresponding to the hydrometer readings in column 2. Values of effective depth were taken from table XI of ASTM D422-61T[1] for hydrometer 152H. The remaining columns in data sheet 1 were determined as follows:

Column 4 = (column 3)/T

Column 5 = $\sqrt{\beta \text{ (column 4)}} = \sqrt{240 \text{ (column 4)}}$

Column 6 = column 2 + composite correction

Column 7 = γ (column 6) = 3.89 (column 6)

The values of the constants, β and γ, were determined and are shown on the data sheet. A plot of column 7 vs log (column 5) yields the particle size distribution curve for Standard Super-Cel (figure 22).

PERMEABILITY: K_3

K_3 values were determined in this study from plots of head loss in units of cm of difference between the right and left leg readings of the bromoform manometer vs. flow rate in ml/sec (column 7 vs. column 4 in Data sheet 2). K_3 is related to the slope of such a plot, and the relationship between K_3 and this slope will be developed here. When clean water is filtered through a clean precoat with no body feed layer present, equation 1 reduces to:

$$H = K_3 Q W_1$$

where: H = head loss through filter cake (ft)
Q = flow rate (gpm/ft^2)
W_1 = precoat weight (#/ft^2)

The assumption was made in the development of equation 1 that the head loss through the filter septum is negligible. This assumption was found to be true for the septum of stainless steel mesh used in the EK filter. No head loss across just the septum could be detected by the bromoform manometer at a flow rate of 2.55 gpm/ft^2, which is the highest flow that can be measured with the flow meter.

Solving the equation above for K_3 yields $K_3 = H/QW_1$. However, this K_3 value varies with temperature, and therefore, is not the constant K_3 value desired. The desired K_3 value can be obtained from the nonconstant K_3 value by use of equation 7. Accordingly:

$$K_3 = H/QW_1 n \quad \ldots\ldots\ldots\ldots \quad (14)$$

where: n = viscosity of the filter effluent (centipoises).

In order to develop the relationship between K_3 and the slope of the curve actually plotted, let:

Δ = difference in manometer leg readings (cm)

q = flow rate (ml/sec)

$m = \Delta/q$ = slope of the straight line plot of Δ vs q

w = weight of precoat diatomite (gm)

The desired relationship is the one relating K_3 to m.

The bromoform used in the manometer had a specific gravity of 2.85. This can be used to relate H and Δ:

$$H = \Delta(2.85 - 1)\left[\frac{0.0328 \text{ ft}}{\text{cm}}\right] = 0.0607\,\Delta$$

The area of the EK filter septum (2 inch diameter) is 0.0218 ft^2. Accordingly:

$$Q = q\left[\frac{0.0002642\ \text{gal}}{\text{ml}}\right]\left[\frac{60\ \text{sec}}{\text{min}}\right]\left[\frac{1}{0.0218\ \text{ft}^2}\right]$$

$$= 0.728q$$

$$W_1 = w\left[\frac{\#}{454\ \text{gm}}\right]\left[\frac{1}{.0218\ \text{ft}^2}\right] = 0.1010\ w$$

Substitution for H, Q, and W_1 of equation 14 above yields:

$$K_3 = \frac{0.825\ \Delta}{q\ \ w\ \ n} = \frac{0.825\ m}{w\ \ n} \quad . . . . (15)$$

Equation 15 is the formula used to compute K_3 from the slope, m, of the straight line plot of Δ vs q (data sheet 2).

The actual data taken for the K_3 determination of D4200/A using the EK filter are illustrated in data sheet 2. In data sheet 2, columns 1, 2, 3, 5, and 6 and the underlined material at the top of the table were recorded either at the beginning of or during the test. Column 4 is simply column 2 divided by column 3, and column 7 is column 6 less column 5.

In order to determine the K_3 value for D4200/A, the values in column 7 (Δ) of table 2 were plotted against the corresponding values in column 4 (q) of data sheet 2. This was done directly on the data sheet. The slope (m) of the resulting straight line was found to be 4.05. K_3 was then determined from equation 15:

$$K_3 = \frac{0.825\ m}{w\ \ n} = \frac{0.825(4.05)}{5.0(0.813)}$$

$$= 0.82\ \text{ft}^5\ \text{min}/\#\ \text{gal}.$$

The value for n at 29.3°C is 0.813 centipoises compared to 1.00 centipoises at 20°C. This is a difference of almost 20%. If the variation of temperature were not accounted for in the determination of K_3 values, it is not hard to see that comparison of K_3 values determined at different temperatures could be discouraging.

DATA SHEET 1. HYDROMETER TEST

HYDROMETER TEST: ASTM D422-61T Run 1

Grade of diatomite Standard Super-Cel Date 9/6/62

Temperature: start 25.0°C, end 25.0°C Initials JHD

Sample weight, W = 30.0 gm Composite correction -4.0

1 Time hr-min	2 Hydrom rdg. R	3 L cm	4 $v_s = L/T$ cm/min	5 $D = \beta v_s$ μ	6 R_c (correct)	7 $P = \gamma R_c$ % finer
9:50a	Beginning of Sedimentation					
9:51	29.2	11.48	11.48	52.6	25.2	98.0
9:52	28.8	11.54	5.77	37.3	24.6	96.5
9:55	26.0	11.7	2.34	23.8	24.0	93.4
10:04	25.5	12.1	0.860	14.4	21.5	86.6
10:20	22.5	12.6	0.420	10.1	18.5	72.0
10:55	18.0	13.3	0.204	7.0	14.0	54.5
2:20p	9.0	14.8	0.0548	3.6	5.0	19.5
5:24	6.5	15.2	0.0335	2.8	2.5	9.7
9:39p	5.0	15.5	0.0218	2.3	1.0	3.9
8:55a	4.8	15.5	0.0112	1.6	0.8	3.1
11:00a	4.3	15.6	0.0103	1.6	0.3	1.2

$$\beta = \frac{30{,}610\ n}{(G-1)} = \frac{30{,}610\ [0.00894]}{[1.14]} = \underline{240}$$

$$\gamma = \frac{62.2\ G}{W\ F\ (G-1)} = \frac{62.2\ [2.14]}{[30.0]\ [1]\ [1.14]} = \underline{3.89}$$

G = specific gravity of the diatomite sample

F = hygroscopic moisture correction factor

n = coefficient of viscosity of water (poises)

DATA SHEET 2. K_3 DETERMINATION WITH EK FILTER

Grade of diatomite D4200/A

Run 99

Precoat 5.0 gm

Investigator DHC

Temperature: Influent 26.2°C

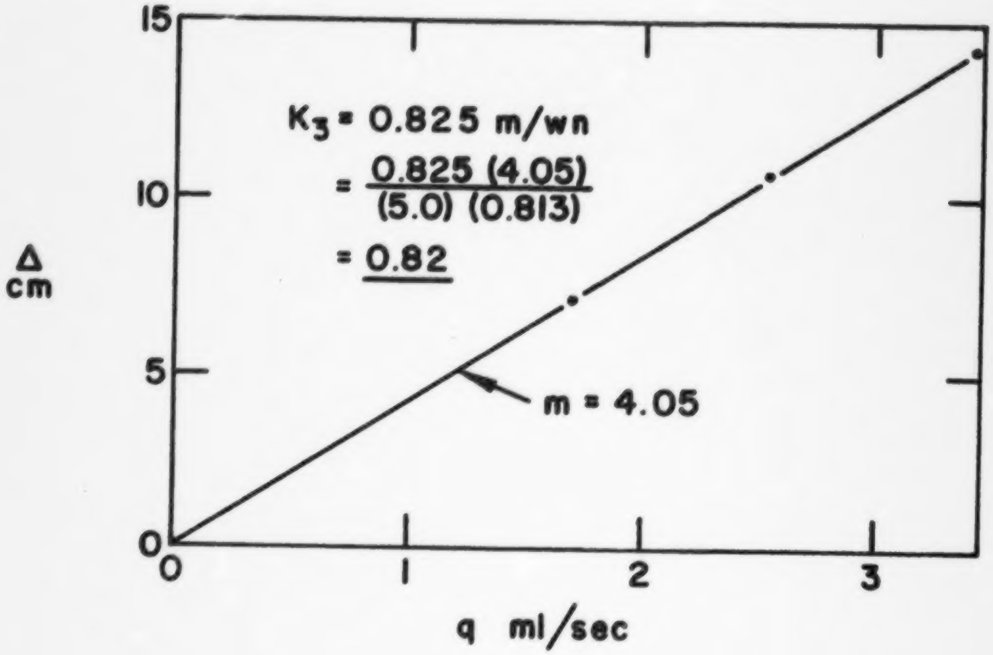
Date 6/17/63

Effluent 29.3°C

Solution dist. H_2O

Septum cleaned before run? Yes

	Flow			Manometer		
1 Rdg.	2 Vol. ml	3 Time sec.	4 Flow, q ml/sec	5 Lt. cm	6 Rt cm	7 Diff, Δ cm
20	442	127.4	3.47	17.2	31.3	14.1
16	397	152.9	2.60	18.9	29.6	10.7
12	231	132.1	1.75	20.7	27.8	7.1



PART IV

STREAMING POTENTIALS IN DIATOMITE FILTRATION OF WATER

C. S. Oulman
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Progress Report

STREAMING POTENTIALS IN DIATOMITE FILTRATION OF WATER

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INTRODUCTION

Electric potentials called streaming potentials are produced when water is filtered through a porous media such as diatomite. Streaming potentials probably do not affect the build-up of head loss in a diatomite filter to any great extent[1], but they are indicative of the electrically charged character of the surface of diatomite in a filter cake.

The surface charge of diatomite is related to the zeta potential of the particles making up the filter cake. The zeta potential in turn can be calculated from measurements involving the streaming potential.

It is useful to know the zeta potential of diatomite used in a filter cake because the applications in which the filter aid is most effective for removing solids from a water depend on the surface charge. If the particles in water contributing to its turbidity have a zeta potential opposite to that of the filter media, coagulation of the solids on the filter aid will take place. This is known as mutual coagulation.

Since the zeta potential of most of the colloidal particles found in natural waters is negative, filter aids used in their filtration should have a positive zeta potential unless the particles can be removed effectively by simple straining. Diatomite filter aids can be given a positive zeta potential by coating them with alum[2], iron, or with a cationic polyelectrolyte.

OBJECTIVES

The purposes of this study were:

1. To determine from streaming potential measurements the zeta potential of representative grades of diatomite used in water filtration.
2. To determine the effect of chemically treated water on the zeta potential of diatomite filter aids.
3. To determine the effect of electropositive materials used for coating diatomite on the zeta potential of coated filter aids.

THEORY

SURFACE CHARGE

A suspension of diatomite in water is electrically neutral, but the suspended particles have an electrical surface charge. The water layer in contact with particles of diatomite has an electrical charge of the opposite sign, so that the net result is electrical neutrality. These charges accumulate as a result of[3]:

1. Preferential adsorption of one kind of ion from the electrolyte in which the particle is suspended.
2. Direct ionization at the surface of the particle followed by migration of one kind of ion into the adjacent water layer.
3. Selective adsorption of hydrogen or hydroxyl ions from the water.

The ions which give rise to the charge in the water layers are held in the vicinity of the particle by an electrostatic attraction for the oppositely charged surface of the particle. These ions are distributed by diffusion in

Thus[4]:

$$\zeta_T = \frac{4\pi\mu kE}{DP}\left(\frac{1}{R} + \frac{4\lambda_s}{d}\right) \text{ - - - - - - } (2)$$

where: ζ_T = the true zeta potential in pure water,

λ_s = specific surface conductance of the particles,

d = mean particle diameter.

If the true zeta potential (ζ_T) is divided by the apparent zeta potential (ζ) the following relationship can be derived:

$$\frac{1}{\zeta} = \frac{1}{\zeta_T} + \frac{4\lambda_s R}{\zeta_T d} \text{ - - - - - - - - - - - - } (3)$$

The true zeta potential and the specific surface conductance can be evaluated by plotting the reciprocal of the apparent zeta potential as a function of the resistivity of the water. The data will plot as a straight line whose intercept is the reciprocal of the true zeta potential if the variations in the apparent zeta potential are caused only by conductance along the particle surface.

TEST PROCEDURES

APPARATUS

A small plexiglass filter equipped with silver-silver chloride electrodes was used as a streaming potential cell in this study (figure 1). Streaming potentials were measured and recorded with a recording potentiometer that was connected across the two electrodes (figure 2).

Head losses were measured with a differential manometer containing bromoform for a manometer fluid. Filtration rates were indicated with a rotameter and were checked volumetrically during each filter run with a graduated cylinder as a check on the rotameter.

A centrifugal pump with a maximum discharge of 7 gpm was used to produce flow in the system. The highest rate of flow used in any filter run was about 0.056 gpm, so the pump was operated at less than 1 percent of its rated discharge. As a result, there was a temperature rise in the water passing through the system of about 3°C.

Glass and copper tubing with 1/4 inch O. D. and Tygon tubing with 1/4 inch I. D. was used throughout the system. The tubing and valves were arranged so that water could either be pumped from the supply tank through the system and to waste or from a recycle tank through the filter and back to the recycle tank.

FILTER RUNS

Filter runs made with the streaming potential filter consisted of three parts:

1. Coating. A slurry of diatomite was recycled through the filter to build up a filter cake.
2. Testing. The filter cake was washed by the test solution in the supply tank. Simultaneously, measurements of both head loss and streaming potentials were made at several different filtration rates. The temperature and electrical resistivity of the filtrate were measured in this part of the filter run. Table I shows the data taken during a typical streaming potential filter run. Figure 3 is the record made by the potentiometer during this run.

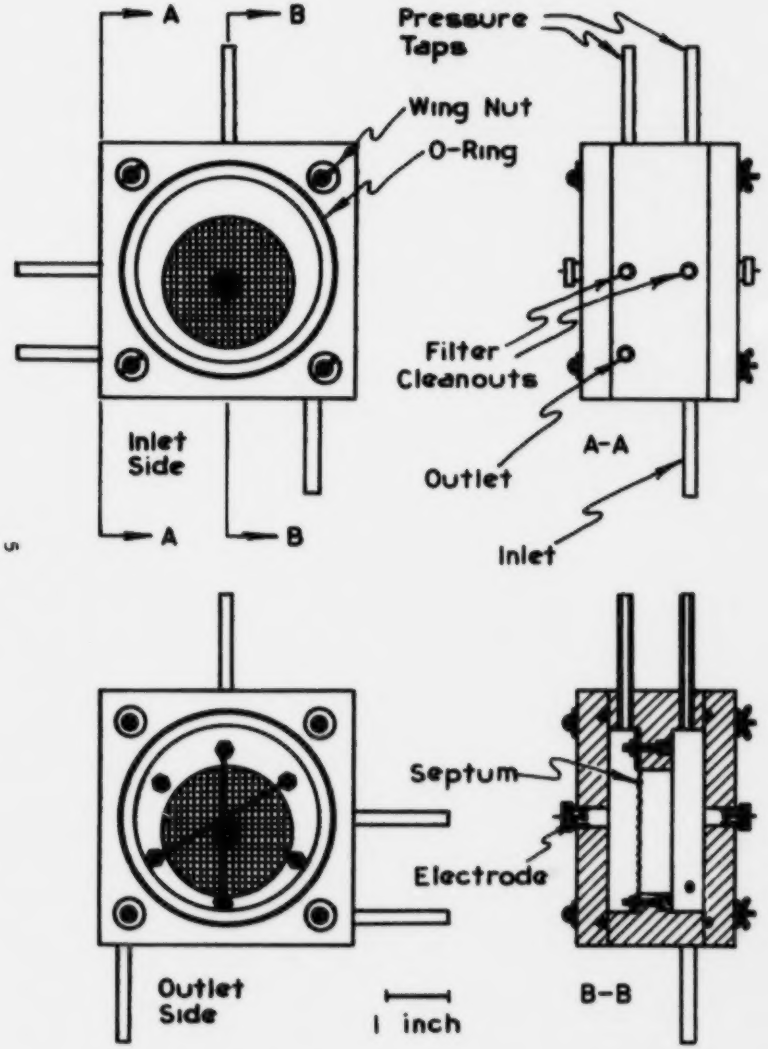

Fig. 1 The streaming potential cell

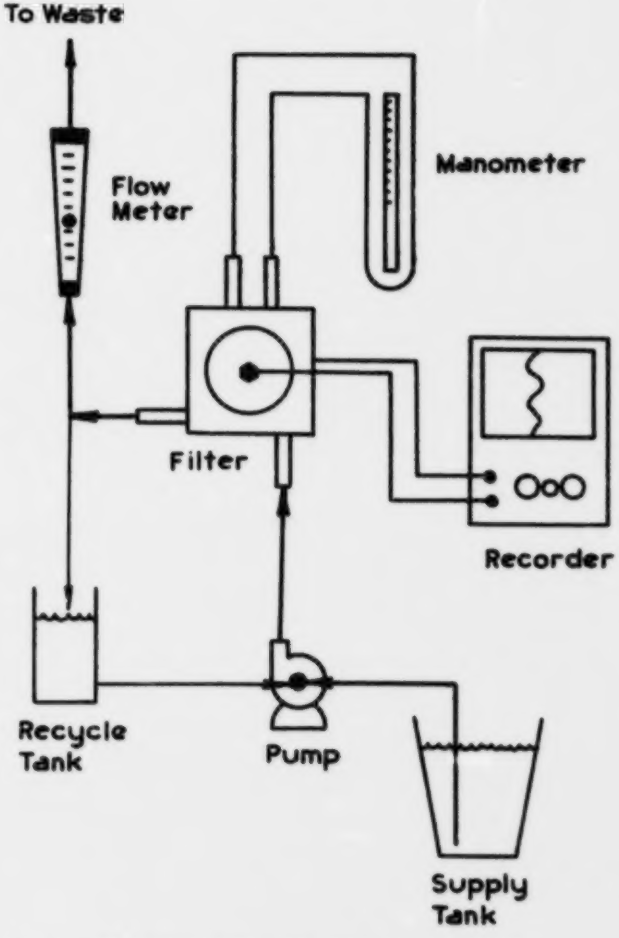

Fig. 2 Flow sheet showing apparatus used for streaming potential measurements.

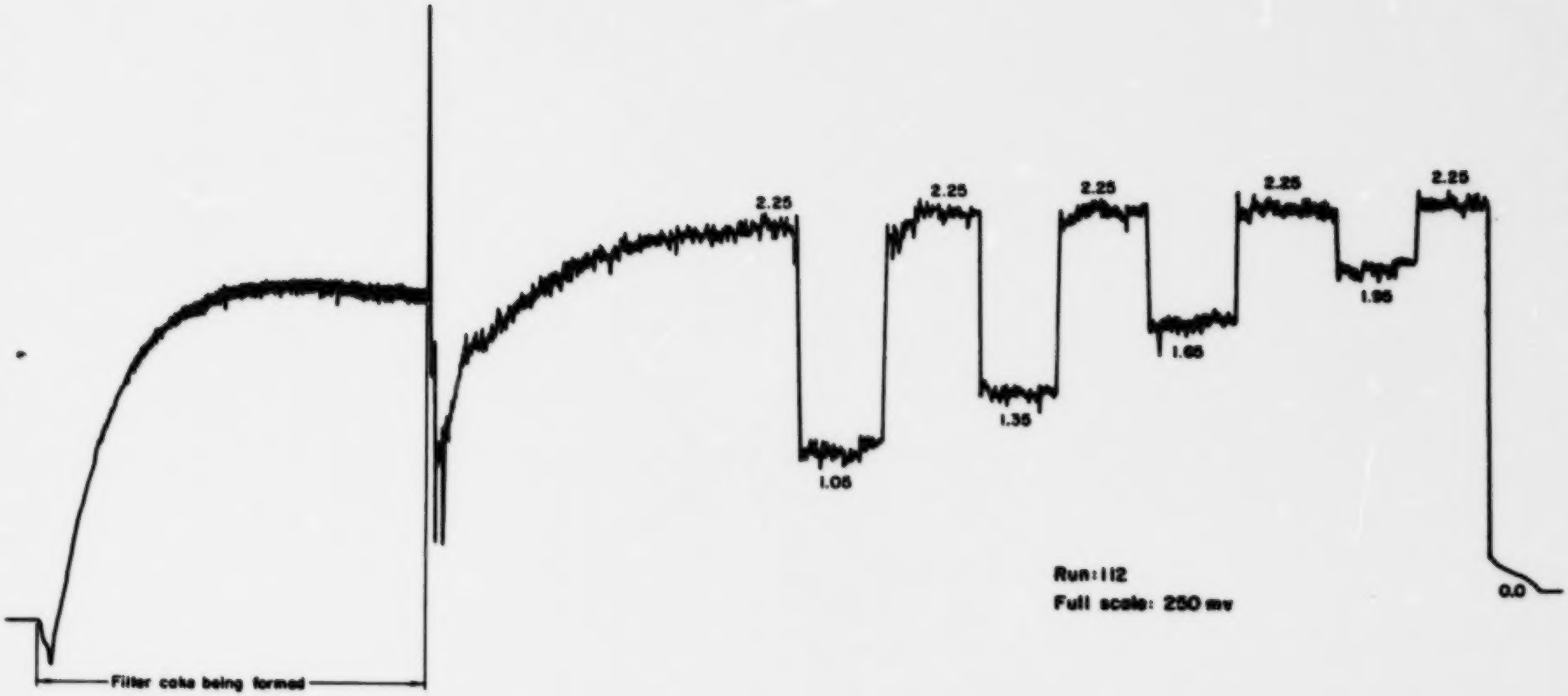

Fig. 3 Streaming potential record for typical filter run

Table I. Data for streaming potential, filter run 103.

Flow meter reading	Bromoform Manometer reading Left leg, cm	Bromoform Manometer reading Right leg, cm	Filtrate resistance, ohms	Filtrate temperature, °C	Flow meter check, ml per min
18	14.3	37.5			
10	21.0	30.8			82
18	14.2	37.5			184
12	19.5	32.3			106
18	14.3	37.4			
14	17.7	34.0			133
18	14.2	37.5	54,000	27.0	
16	16.0	35.7			158
18	14.2	37.5			
0	25.9	25.9			

3. Cleaning. The used diatomite filter cake was flushed out of the filter through the filter cleanout on the inlet side of the filter.

INTERPRETATION OF DATA

Four variables were measured during each streaming potential filter run, streaming potentials, head losses, filtrate resistivity and filtrate temperature. The streaming potential and head loss varied with flow rate, but the ratio of one to the other was constant for all flow rates.

The electrodes delivered a small but variable potential of their own. Therefore, the potential indicated by the recording potentiometer was the sum of the electrode potential and the streaming potential. For this reason it was not possible to determine the streaming potentials directly from the null potential of the recorder. Instead, the difference in potential between that indicated for the highest filtration rate and that for lower filtration rates was used. A difference in streaming potential (ΔE) and a difference in head loss (ΔP) was measured for each difference in streaming potential. Because the ratio between streaming potential and head loss is constant:

$$\frac{\Delta E}{\Delta P} = \frac{E}{P}$$

Table II shows head losses calculated for the data given in Table I. Differences in streaming potential taken directly from the potentiometer recording (figure 3) and differences in head loss calculated from those given in Table II are shown in Table III. These were used in calculating the values of E/P shown. The average value of E/P was used for calculating the zeta potential.

Since the temperature and resistivity of the filtrate remains relatively constant during a filter run, they were usually measured only once during a run. The temperature of the filtrate was used to determine the viscosity and the dielectric constant of the test solution. It was assumed that these properties would be the same for the test solution as for pure water. These data were then used to calculate the apparent zeta potential of the diatomite using equation 1. For example:

$$\zeta = \frac{-(4\pi)(0.8545 \times 10^{-3})(8.99 \times 10^{9})(91.6)}{(77.2)\ (1441)\ (3000)} = -21.6 \text{ mv}$$

where: $\mu = 0.8545 \times 10^{-3}$ kgm per meter sec @ 27°C.
$E/P = 91.6$ mv per ft. H_2O
$D = 77.2$ @ 27°C
$R = 1441$ ohm-meters

In this computation the electrical resistivity was based on a conductivity cell constant determined by test of 37. 5 meters^{-1}. The constant 3000 is the conversion factor from head loss in feet of water to MKS units.

Table II. Head losses for streaming potential filter run 103.

Flow meter reading	Bromoform Manometer reading Left leg, cm	Right leg, cm	Difference in readings, cm	Head loss*, ft H_2O
18	14. 3	37. 5	23. 2	1. 409
10	21. 0	30. 8	9. 8	0. 595
18	14. 2	37. 5	23. 2	1. 414
12	19. 5	32. 2	12. 8	0. 777
18	14. 3	37. 4	23. 1	1. 402
14	17. 7	34. 0	16. 3	0. 990
18	14. 2	37. 5	23. 3	1. 414
16	16. 0	35. 7	19. 7	1. 195
18	14. 2	37. 5	23. 3	1. 414
0	25. 9	25. 9	0. 0	0. 000

* (Difference in readings, cm) x 6. 07 x 10^{-2} = ft. of water

Table III. Values for streaming potential filter run 103.

Flow rate change, meter readings	Head loss Average for higher flow, ft H_2O	Value for lower flow, ft H_2O	Difference in head loss, ft H_2O	Difference in streaming potentials, mv	E/P mv per, ft H_2O
18-10-18	1. 412	0. 595	0. 817	75. 0	91. 8
18-12-18	1. 408	0. 777	0. 631	59. 5	94. 3
18-14-18	1. 408	0. 990	0. 418	37. 0	88. 5
18-16-18	1. 414	1. 195	0. 219	20. 5	93. 6
18- 0	1. 414	0. 000	1. 414	127. 0	89. 9
Total					458. 1
Average					91. 6

TEST RESULTS

ZETA POTENTIAL OF DIATOMITE

The zeta potential of flux calcined diatomite varied with the resistivity of the water used in the streaming potential filter run. The zeta potential also varied with the kind of diatomite tested and the kind of solution used. Zeta potentials of 8 grades of flux calcined diatomite tested with distilled water were determined (table IV). The zeta potentials of 2 grades of coated diatomite tested with distilled water were measured (table V). The flux calcined grades had a negative zeta potential; the coated grades had a positive zeta potential.

The flux calcined grades of diatomite were shown to be negatively charged, and the two coated grades were positively charged when tested in a filter cake by streaming potential measurements. Electrophoretic measurements, however, showed that the direction of travel in an electric field was the same for a coated filter aid as that of a flux calcined filter aid. Thus, each had a negative charge according to conventional measuring techniques.

This showed that the coated filter aid consisted of a positively charged precipitate surrounding a negatively charged diatomite particle or particles. Because the coating was sufficiently cohesive to resist erosion by hydrodynamic forces it exhibited a positive charge according to streaming potential measurements. The coating did not adhere to the diatomite particle strongly enough, however, to prevent the negatively charged diatomite particle from being pulled out of its positively charged coating by electrical forces during electrophoretic measurements.

The zeta potentials of 5 grades of flux calcined diatomite tested with deionized water were measured (table VI). Because the resistivity of deionized water is much greater than that of distilled water, it is difficult to compare the zeta potentials of diatomite tested in deionized water (table VI) with the zeta potentials of diatomite tested in distilled water (table IV, figure 4). These results can be compared, however, by means of the true zeta potentials. The true zeta potential of the diatomite tested with distilled water was 55.1 mv; the true zeta potential of the diatomite tested with deionized water was 39.9 mv. These values were calculated by means of their least-square estimators[5].

The zeta potential of four grades of diatomite tested with deionized water and solutions of 5 salts prepared from the same deionized water were measured (table VII). The true zeta potentials and the specific surface conductances were determined from these tests (table VIII). These values were calculated by averaging together the results of the individual runs with each kind of salt without regard for the grade of diatomite used. The specific surface conductances were based on the following mean particle sizes[6]: Speedex, 13 microns; Celite 503, 13 microns; Dicalite 4200, 19 microns; Celite 545, 21 microns.

There were significant differences both in the true zeta potentials and the specific surface conductances depending on what cations were present in the water. The kind of anion did not seem to have any significant effect.

The zeta potential of a single grade of diatomite, Celite 535, tested with solutions

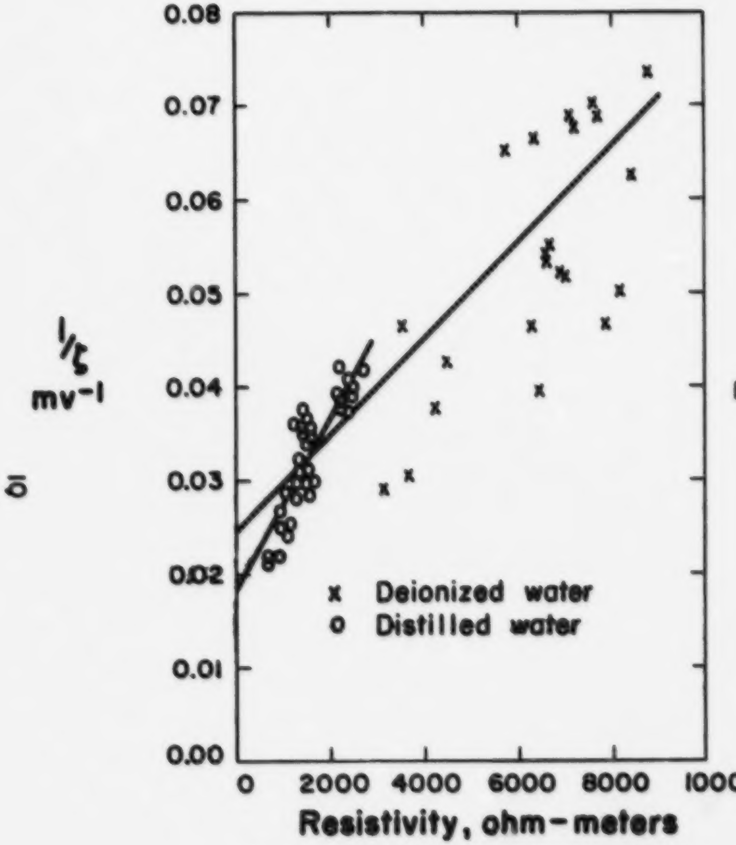

Figure 4. Reciprocal zeta potentials of flux calcined grades of diatomite as a function of the resistivity and kind of water filtered.

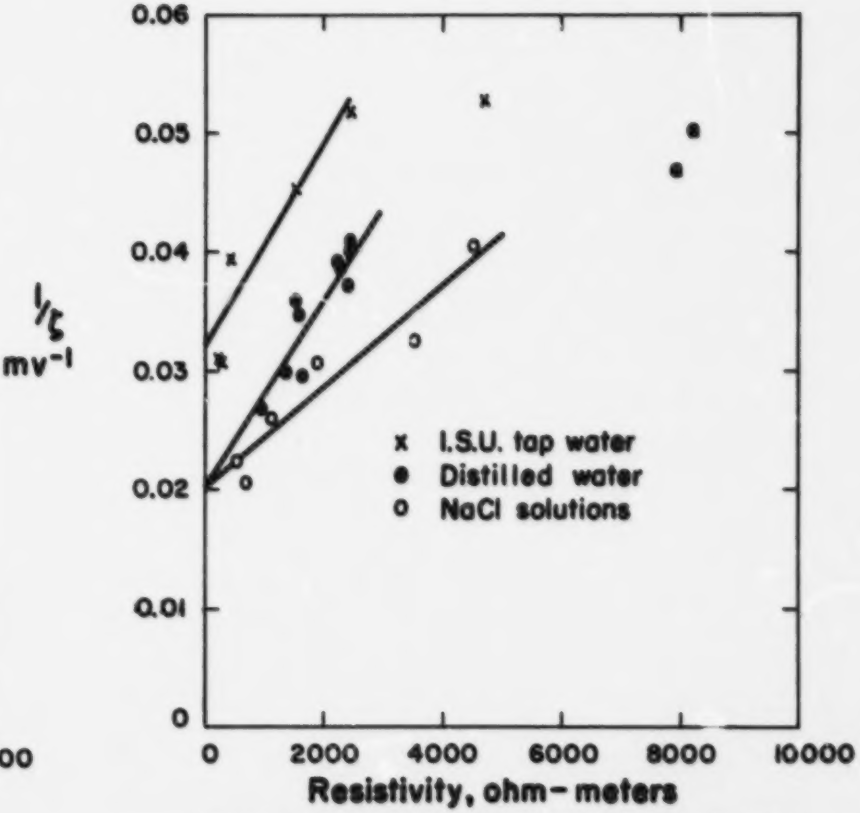

Figure 5. Reciprocal zeta potentials of Celite 535 as a function of the resistivity and kind of water filtered.

of sodium chloride in deionized water and Iowa State University tap water in deionized water are given in tables IX and X, respectively. The tests with sodium chloride and deionized water were made to determine the effect of different concentrations of a salt solution on a specific grade of filter aid. Figure 5 shows the results of these tests with those obtained with distilled water (table IV). The curves for the solutions of sodium chloride and for tap water were straight lines only in those ranges of concentration where the added material had a major effect on the resistivity of the solution.

The true zeta potential of Celite 535 was about the same for either distilled water or deionized water made more conducting by adding sodium chloride but was lower for solutions containing Iowa State University tap water. The specific surface conductance was about the same for solutions of either sodium chloride or tap water but was higher with distilled water (table XI). Thus, the kind of water filtered through diatomite affected both the zeta potential and the surface conductance of the diatomite.

Table IV. Zeta potentials determined by streaming potential measurements of 8 grades of flux calcined diatomite using distilled water

Grade of diatomite	Run number	Apparent zeta potential, mv	Reciprocal zeta potential, mv^{-1}	Filtrate resistivity, ohm-meters
Celatom FW 20	119	-31.9	-0.0313	1534
	115	-28.5	-0.0351	1532
Celatom FW 60	123	-35.7	-0.0280	1305
	118	-33.6	-0.0298	1572
	110	-32.3	-0.0310	1360
Celite 503	124	-34.8	-0.0287	1571
	7	-34.6	-0.0289	1033
	121	-29.2	-0.0342	1519
	5	-27.7	-0.0361	1290
	6	-27.6	-0.0362	1360
	112	-26.5	-0.0377	1441
Celite 535	8	-37.0	-0.0270	947
	116	-33.7	-0.0297	1620
	109	-33.2	-0.0301	1360
	58	-28.8	-0.0347	1566
	57	-27.8	-0.0360	1550
	59	-26.8	-0.0373	2400
	56	-26.5	-0.0377	2260
	55	-26.3	-0.0380	2235
	107	-25.0	-0.0400	2440
	108	-24.4	-0.0410	2430
Celite 545	105	-47.2	-0.0212	684
	104	-45.7	-0.0219	682
	9	-39.5	-0.0253	969
	103	-25.9	-0.0386	2220
	102	-25.8	-0.0388	2500
	106	-25.5	-0.0392	2370
Celite 560	11	-45.1	-0.0222	963
	10	-41.0	-0.0244	1080
	4	-27.3	-0.0366	1510
	98	-25.3	-0.0395	2180
	101	-25.0	-0.0400	2500
	100	-23.8	-0.0420	2760
	99	-32.6	-0.0424	2220
Dicalite Speedex	120	-28.6	-0.0350	1491
	114	-28.1	-0.0356	1510
Dicalite 4200	122	-39.3	-0.0254	1111
	117	-33.6	-0.0298	1572
	111	-30.9	-0.0324	1386

Table V. Zeta potentials determined by streaming potential measurements of 2 grades of coated diatomite using distilled water

Grade of diatomite	Run Number	Apparent zeta potential, mv	Reciprocal zeta potential, mv^{-1}	Filtrate resistivity, ohm-meters
Sorbo-Cel	11	+46.3	+0.0216	978
	13	+35.1	+0.0285	9[illegible]
	12	+34.7	+0.0288	973
	14	+34.4	+0.0291	910
Celite 545, Mix B	17	+29.8	+0.0356	654
	15	+28.6	+0.0350	740
	3	+26.8	+0.0373	896
	16	+24.6	+0.0407	682

Table VI. Zeta potentials determined by streaming potential measurements of 5 grades of flux calcined diatomite using deionized water

Grade of diatomite	Run Number	Apparent zeta potential, mv	Reciprocal zeta potential, mv^{-1}	Filtrate resistivity, ohm-meters
Celite 503	24	-21.4	-0.0467	6350
	19	-15.3	-0.0654	5740
	37	-14.8	-0.0676	7190
	38	-14.5	-0.0690	7710
	20	- 8.3	-0.1205	5350
Celite 535	136	-21.2	-0.0472	7900
	128	-19.9	-0.0503	8190
Celite 545	27	-34.1	-0.0293	3190
	28	-32.6	-0.0307	3670
	18	-26.4	-0.0379	4250
	29	-21.4	-0.0467	3540
	33	-19.3	-0.0518	6970
	32	-19.2	-0.0521	6990
	23	-14.5	-0.0690	7100
	30	-13.6	-0.0703	7600
Dicalite Speedex	25	-18.4	-0.0543	6640
	31	-15.0	-0.0667	6360
	35	-13.5	-0.0741	8800
	36	-11.9	-0.0840	8450
Dicalite 4200	26	-25.3	-0.0395	6410
	21	-23.3	-0.0429	4490
	22	-18.7	-0.0535	6640
	39	-18.1	-0.0552	6680
	34	-15.9	-0.0692	8450

Table VII. Zeta potentials determined by streaming potential measurements of 4 grades of flux calcined diatomite filter aids using deionized water and solutions of 5 salts

Salt in solution	Grade of diatomite	Run number	Apparent zeta potential, mv	Reciprocal zeta potential, mv^{-1}	Filtrate resistivity, ohm-meters
None	Speedex	36	-11.9	-0.0840	8450
NaCl	Speedex	36	-34.8	-0.0287	1200
None	Celite 503	37	-14.8	-0.0676	7190
NaCl	Celite 503	37	-35.0	-0.0286	1200
None	Celite 545	23	-14.5	-0.0690	7100
Na_2SO_4	Celite 545	23	-31.6	-0.0316	1190
None	Dicalite 4200	26	-25.3	-0.0395	6410
Na_2SO_4	Dicalite 4200	26	-44.0	-0.0227	1220
None	Celite 545	32	-19.2	-0.0521	6990
$MgCl_2$	Celite 545	32	-31.4	-0.0318	590
None	Celite 503	12	-15.3	-0.0654	5740
$MgSO_4$	Celite 503	12	-23.4	-0.0427	675
None	Speedex	31	-15.0	-0.0667	6640
$MgSO_4$	Speedex	31	-27.1	-0.0369	685
None	Celite 545	30	-13.6	-0.0703	7600
$MgSO_4$	Celite 545	30	-29.6	-0.0338	650
None	Dicalite 4200	22	-18.7	-0.0535	6640
$FeSO_4$	Dicalite 4200	22	-15.0	-0.0667	695
None	Celite 503	24	-21.4	-0.0467	6350
$FeSO_4$	Celite 503	24	-18.3	-0.0546	660
None	Speedex	35	-13.5	-0.0741	8800
$FeSO_4$	Speedex	35	-20.0	-0.0500	695

Table VIII. True zeta potential and specific surface conductance determined by streaming potential measurements of 4 grades of flux calcined diatomite filter aids using deionized water and solutions of 5 salts

Salt in solution	True zeta potential, mv	Specific surface conductance, $ohms^{-1}$
NaCl	-48.7	1.1×10^{-9}
Na_2SO_4	-47.5	1.1×10^{-9}
$MgCl_2$	-33.4	0.6×10^{-9}
$MgSO_4$	-29.4	0.6×10^{-9}
$FeSO_4$	-18.3	0.0

Table IX. Zeta potentials determined by streaming potential measurements of Celite 535 using solutions of sodium chloride in deionized water

Moles of NaCl per liter of water	Run Number	Apparent zeta potential, mv	Reciprocal zeta potential, mv^{-1}	Filtrate resistivity, ohm-meters
0.0001	131	-48.8	-0.0250	698
0.00004	125	-43.3	-0.0225	516
0.000023	126	-38.3	-0.0262	1132
0.0000126	127	-34.3	-0.0309	1890
0.0000104	129	-30.5	-0.0328	3550
0.0000054	130	-24.7	-0.0405	4540
0.0	136	-21.2	-0.0471	7900
0.0	128	-19.9	-0.0502	8190

Table X. Zeta potentials determined by streaming potential measurements of Celite 535 using solutions of Iowa State University tap water in deionized water

Percent tap water in deionized water	Run number	Apparent zeta potential, mv	Reciprocal zeta potential, mv^{-1}	Filtrate resistivity, ohm-meters
3.69	137	-32.3	-0.0310	251
1.845	132	-25.3	-0.0395	453
0.497	135	-22.0	-0.0455	1560
0.295	134	-19.2	-0.0520	2410
0.0626	133	-18.8	-0.0530	4720
0.0	136	-21.2	-0.0471	7900
0.0	128	-19.9	-0.0502	8190

Table XI. True zeta potential and specific surface conductance determined by streaming potential measurements of Celite 535 using three different wash solutions

Wash solution	True zeta potential, mv	Specific surface conductance, $ohms^{-1}$
Distilled water	-49.4	1.6×10^{-9}
Sodium Chloride in* deionized water	-49.8	0.9×10^{-9}
I. S. U. tap water** in deionized water	-31.1	1.0×10^{-9}

*Based on first 6 lines of data in Table IX.
**Based on first 4 lines of data in Table X.

REVERSAL OF ZETA POTENTIAL

The zeta potential of diatomite was reversed from negative to positive by treating the diatomite with chemical solutions containing polyvalent cations. The diatomite could be successfully treated in either one of two ways.

Treatment while filtering

The zeta potential of diatomite in a filter cake was permanently lowered by filtering a solution containing aluminum sulfate, aluminum chloride,or ferric sulfate through the cake in the filter.

When this treatment with small amounts of such solutions was repeated several times, the zeta potential of the diatomite was changed progressively from negative to positive (table XII).

Treatment before filtration

Before some cakes were formed, diatomite was treated with a solution containing polyvalent cations. This was done by mixing the solution with diatomite in a beaker. The polyvalent cation aluminum chloride changed the zeta potential of diatomite from negative to positive (table XIII). Less salt was required to change the particle charge when treatment was before filtration than when treatment was within the filter.

Treatment before filtration was also effective for reversing the zeta potential of diatomite with a cationic polyelectrolyte. The zeta potential of Celite 545 was reversed from negative to positive by treatment with a very dilute solution of unknown concentration of Union Carbide Resin C-149. The zeta potential of the filter aid coated with this cationic polyelectrolyte was about +43 mv.

Table XII. Reversal of the zeta potential of diatomite by treatment with aluminum and ferric salts in the filter

Salt used	Grade of Diatomite	Run number	Metal Ion to diatomite ratio, percent by weight	Zeta potential, mv
$Fe_2(SO_4)_3$	Celite 545	40	0.00	-30
			0.55	- 2
			1.27	0
			1.79	+ 1
			2.10	+ 1
$Al_2(SO_4)_3$	Celite 545	18	0.000	-26.4
			0.030	-17.2
			0.053	- 2.7
			0.082	+13.0
			0.118	+22.6
			0.176	+30.0
	Celite 503	38	0.000	-14.5
			0.039	- 8.7
			0.087	+17.8
			0.297	+31.4
	Dicalite 4200	39	0.000	-18.1
			0.003	-19.8
			0.014	-10.3
			0.025	0.0
			0.036	+13.2
			0.086	+29.1
$AlCl_3$	Celite 503	20	0.000	- 8.3
			0.086	+ 8.7
			0.129	+15.1
			0.173	+19.0
			0.223	+18.5
	Speedex	25	0.000	-18.4
			0.030	-14.1
			0.076	+ 5.6
			0.146	+17.0
			0.209	+21.8
			0.308	+25.0
	Dicalite 4200	34	0.000	-15.9
			0.031	+ 4.2
			0.052	+ 8.5
			0.079	+19.6
			0.121	+26.9

Table XIII. Reversal of the zeta potential of Celite 535 by treatment with aluminum chloride before filtration

Run number	Metal Ion to diatomite ratio, percent by weight	Zeta potential, mv
65	0.003	-28.9
66	0.003	-30.0
67	0.003	-29.3
68	0.006	-28.4
69	0.007	-23.9
70	0.007	-22.5
71	0.007	-21.1
63	0.008	0.0
64	0.008	- 3.3
76	0.008	+ 7.1
72	0.011	-11.3
75	0.011	+14.1
73	0.014	+ 9.2
74	0.019	+25.2
80	0.027	+31.0
60	0.027	+29.4
61	0.027	+37.8
62	0.027	+32.6
81	0.040	+24.5
82	0.040	+29.5
87	0.040	+28.8
83	0.050	+26.7
88	0.050	+24.5
89	0.050	+26.7
84	0.074	+27.3
85	0.074	+27.3
86	0.074	+26.0

APPLICATIONS IN PRACTICAL FILTRATION

With surface waters, both the load of turbidity and the filtrability of the water can be highly variable. It is in the filtration of these waters that flux calcined diatomite has been the least effective; and it is here, also, that electro-positively coated diatomite has been most effective.

When coagulants are not used, or when less than the optimum quantity is used, the load of turbidity left in the water after sedimentation is greater than when the optimum dosage is used. The turbidity that is left must be removed by filtration, and the filtrability of this "under-coagulated" water is related to the turbidity initially present in the water. When the coagulant dosage is less than the optimum the water filtrability is characteristic of the raw water; when the dosage is greater than optimum the filtrability is characteristic of the coagulant carry-over (figure 6).

When more than the optimum amount of coagulant is used, the load is increased, but the filtrability of the water is less variable. With "over-coagulated water", the filtrability is characteristic of the coagulant floc that is carried over to the filters. Since the filtrability of the coagulant floc is subject to prior study in the laboratory, filtration results are more predictable here than they are when "under-coagulated water" is being filtered.

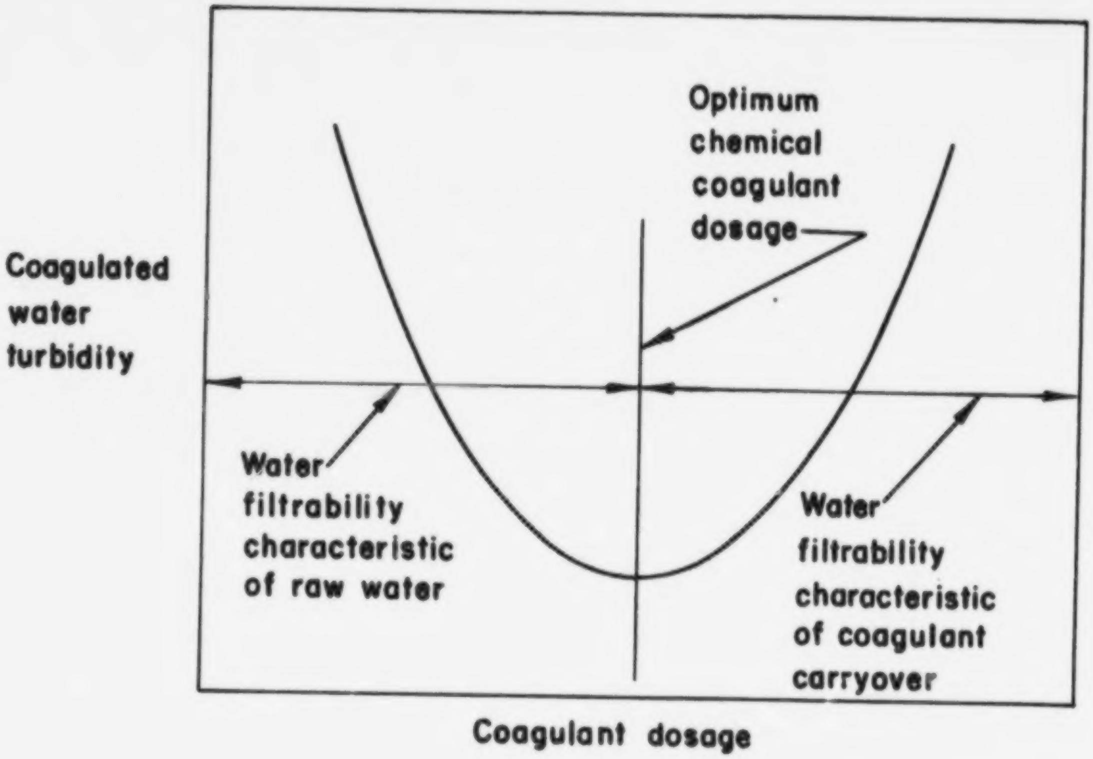
Optimum chemical coagulant dosage
Coagulated water turbidity
Water filtrability characteristic of raw water
Water filtrability characteristic of coagulant carryover
Coagulant dosage

Fig. 6 Relationship between coagulated water turbidity and coagulant dosage as they effect filtration

As was pointed out earlier, mutual coagulation is believed to be responsible for the removal of turbidity in filtration if the particles in water contributing to its turbidity have a zeta potential opposite to that of the filter media. Since the zeta potential of most of the colloidal particles found in natural waters is negative, filter aids used in their filtration should have a positive zeta potential, unless the particles can be removed effectively by simple straining.

Diatomite filter aids can be given a positive zeta potential by either pre-treating them with alum, or with a cationic polyelectrolyte, before the filter cake is formed or by filtering a dilute solution of the polyvalent material through the filter cake after it has been formed. This has been demonstrated in this study. These filter aids would be useful in the filtration of "under-coagulated" waters. Conversely, if the water treatment with alum is carried beyond the optimum, the remaining colloids will be left with a positive zeta potential and will be removed more effectively by a negatively charged diatomite filter cake.

SUMMARY AND CONCLUSIONS

Some colloidal particles too small to be removed by mechanical straining during filtration can be removed by mutual coagulation when the filter aid and the colloid carry opposite electric charges. The charge of a particle is related to its zeta potential, which can be determined by several different methods. In one method the electrical potentials, called streaming potentials, are measured. These potentials are generated when water is filtered through a porous medium consisting of the particles in question. This method was selected for studying the electric charge on diatomite, because the test conditions are the same as those when a liquid is being filtered through diatomite.

One purpose of this study was to determine the zeta potential of flux calcined and electropositively coated grades of diatomite filter aids. The zeta potential of flux calcined diatomite was negative as was expected. Electropositively coated grades of diatomite have been chemically treated with aluminum salts by a patented process which imparts a positive charge to the diatomite. The zeta potentials of these grades of filter aid were found to be positive. The positive zeta potential was caused by a precipitate of aluminum hydroxide surrounding or coating the particles of diatomite in the filter cake. When tested in electrophoresis apparatus however, the electropositive coatings were displaced from the filter and by the application of the external electrical charge used to measure particle mobility.

Another purpose of this study was to determine the effect of ions in water on the zeta potential of diatomite. Sodium ions lowered the specific surface conductance of diatomite but did not seem to have much of an effect on the true zeta potential. Magnesium ions lowered both the true zeta potential and the specific surface conductance. Ferrous ions lowered the true zeta potential still further and reduced the specific surface conductance to zero. Chloride and sulfate ions, in combination with the previously mentioned cations, had little or no effect on either the true zeta potential or the specific surface conductance.

Aluminum and ferric ions and at least some of cationic polyelectrolytes reversed the zeta potential of diatomite from negative to positive. Diatomite filter aids were given a relatively high (about 50 mv) and permanently positive zeta potential by treatment with either aluminum salts or some cationic polyelectrolytes. Ferric salts were less effective and left the filter aid with a low (about +1 mv) but permanently positive zeta potential.

Several conclusions can be drawn about the use of streaming potential measurements for determining the zeta potential of diatomite filter aids:

1. The zeta potential of a filter aid can be determined from streaming potential measurements made during filtration with distilled or deionized water.

2. The zeta potential of a filter aid can not ordinarily be determined directly from streaming potential measurements made during filtration of a natural water because the low resistivity of natural water causes the streaming potential to be diminished in size. Techniques similar to those used in assembling the data for table X and the plotting method used in figure 5 can be used to determine the true zeta potential of diatomite in the filtration of these waters.

3. Streaming potential methods using distilled or deionized water are useful for determining the amount of chemical needed for reversing the zeta potential of diatomite filter aids. Since electrophoresis did not distinguish a difference in the signs of the zeta potentials of coated and non-coated filter aids, streaming potential methods are the most practical method to use.

Several conclusions can also be drawn about the zeta potential of diatomite in chemically treated waters and how filtration practice is affected:

1. The true zeta potential of diatomite in filter cakes is related to the kind of cations in the water. Thus, in general, sodium ions do not change the true zeta potential of diatomite filter aids; magnesium ions make the true zeta potential less negative; and ferrous ions make the true zeta potential even less negative. Aluminum and ferric ions and cationic polyelectrolytes reverse the zeta potential of diatomite and temporarily make it strongly positive.

2. The zeta potential of diatomite can be permanently reversed by treatment with dilute solutions of aluminum salts or cationic polyelectrolytes. This treatment can be given while the slurry of diatomite is first being prepared before precoating the filter or while the solution is being filtered through the filter cake. Less cationic material is required if the coating is applied before precoating the filter. Electropositive filter aids can be prepared easily and cheaply as needed from the standard grades of flux calcined diatomite available from any manufacturer. Where diatomite filters are used to filter an alum treated water, the diatomite becomes electropositively coated without any special effort.

3. Ferric salts are less effective for producing an electropositively charged diatomite filter aid either on a commercial basis or in the field where iron bearing waters are being filtered. As diatomite becomes coated with a precipitate of ferric hydroxide, the particles making up the filter cake become nearly electrically neutral. The iron needed to neutralize the surface charge of the diatomite is only 1.3 percent by weight expressed as an iron to diatomite ratio in the filter cake. The rest of the iron must be removed by mechanical straining.

ACKNOWLEDGEMENTS

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PART V

COATINGS FOR FILTER AIDS

C. S. Oulman
Donald E. Burns
E. R. Baumann

Progress Report

COATINGS FOR FILTER MEDIA*

by

Charles S. Oulman, Donald E. Burns
and
E. Robert Baumann

This work was supported by the Iowa Engineering Experiment Station in part through funds made available by Research Grant WP-00196 from the Division of Water Supply and Pollution Control, Public Health Service.

*Paper to be presented at the 84th Annual Conference of the American Water Works Association in Toronto, Canada, on June 3, 1964.

Project 509-S
May, 1964

IOWA
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COATINGS FOR FILTER MEDIA

by

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PROGRESS REPORT
Project 509-S
of the

Iowa Engineering Experiment Station
Iowa State University
Ames, Iowa

Research Grant WP - 00196 - 04
U. S. Public Health Service
Division of Water Supply and Pollution Control

DESIGN REQUIREMENTS
OF MUNICIPAL DIATOMITE FILTERS

May 1, 1964

COATINGS FOR FILTER MEDIA

by

Charles S. Oulman, Donald E. Burns

and

E. Robert Baumann

One process used for removing particulate matter from water is filtration. If the particles are larger than the interstitial openings of the filter media, the particles are removed by mechanical straining. This is the usual way that particles are removed in a filter. Particles that are too small to be removed by mechanical straining will pass on through the filter if they are not adsorbed on the surfaces of the particles of the filter media.

The surfaces of typical materials used as media for filtering water are not particularly adsorptive. Sand and diatomite, forms of silica, have low adsorptive capacities as does anthracite coal, a form of carbon used as a filter media. One way of making a relatively non-adsorbing material more adsorptive is to coat it with a more adsorptive material. The coating material may not have enough structural stability to act as a filter media by itself and the supporting media, though structurally stable, may be capable of removing particulate matter only by mechanical straining. However, together they may form a stable, adsorptive media capable of removing particles that are both larger and smaller than the interstitial openings of the coated media.

PREVIOUS RESEARCH

In 1936, Cummins[1] patented a process for giving diatomite an electropositive coating to improve its value as a filter media. He claimed that diatomite treated with alum was significantly more effective than non-coated diatomite for removing suspended solids from river water. Diatomite coated with alum has been shown to be more effective than non-coated diatomite for removing turbidity, coliforms, and color-colloids from water[2].

Filter media used in the Pit-Con and Micro-Floc filtration processes are similar to sand in size. An organic polyelectrolyte is used in these processes as a secondary coagulant. It is added to the water being filtered as it enters the filter media. The controlled use of the secondary coagulant reduces the amount of alum needed as the primary coagulant.

Previous research at Iowa State University[3] has shown that diatomite coated with alum and with organic polyelectrolytes have similar electrokinetic properties. Practically all particulate matter in contact with water has a negative zeta potential, but diatomite completely coated with alum, ferric salts, and one cationic organic polyelectrolyte was found by testing to have a positive zeta potential with water in the neutral pH range. The electropositive coating could be formed either by mixing the coagulant with the diatomite in water before forming the cake or by filtering a solution containing the coagulant through the filter media after the cake had been formed.

The filter media used in the Pit-Con and Micro-Floc processes are therefore probably coated by the organic polyelectrolyte used as the secondary coagulant. The increased removal of suspended solids is probably brought about by adsorption of fine flocculated solids on particles of the filter media.

OBJECTIVES OF THIS STUDY

Diatomite coated with alum is less permeable to the flow of water than the same grade of diatomite not so coated. Coarse grades of coated diatomite, however, are still somewhat more permeable than finer grades of diatomite with similar turbidity, coliform, and color-colloid removal capabilities. Therefore, in terms of lower head losses, there is an advantage in using an alum coated filter media.

The objectives of this study have been to find and evaluate the properties of synthetic organic polyelectrolytes for coating diatomite. The three tested were cationic polyelectrolytes. They have been evaluated in terms of the amount needed to form a coating, of the effect that the coatings have on the hydraulic permeability of the filter cake formed, and of the effect of pH of the water being filtered on properties of coated media. Those coated filter media that have not been made materially less permeable by the coating will be field tested to evaluate their effectiveness for removing suspended solids from water.

THEORY

The interstices in a filter media form a tortuous series of inter-connected passageways through which suspended solids-laden water must pass as it is filtered. Because of the frequent changes of direction and cross section in the passageways, particles in suspension will come quite close to the surface of the particles of filter media which form the walls of the interstices.

The suspended solids will not likely make direct particle-to-particle contact with the filter media because the water in the vicinity of the particle surface is not easily penetrated. Research has shown that the heat required to evaporate the water wetting the surface of silica approaches the heat required to evaporate water from ice. The water layer surrounding a clay colloid and a sand grain is highly ordered and ice-like near the water-particle interface.

The degree of order diminishes and freedom of molecular movement increases with distance from the wetted surface. In liquid water flowing through the interstices, however, there is some order to the molecular association of water molecules with each other. Hydrogen bonding gives water molecules an interconnected tetrahedrally bonded three dimensional network type of structure. The bonds in this network are constantly being disrupted and reformed as the water rushes through the openings in the filter media conforming to the shape of the spaces it fills.

The probabability of water molecules remaining associated with each other for a long period of time in the main stream of flow is very low. The probability for breaking hydrogen bonds between water molecules in flowing water is very high. Near the surface of a particle, however, the probability of breaking these bonds is very low.

The probability that a particle smaller in diameter than the interstitial openings of a filter media will be removed in filtration by adsorption is equal to the product of its probability of being adsorbed on the filter media and its probability of not being desorbed. The probability that a particle will be adsorbed on a filter media is a function of the probability that the particle will come in contact with the surface of the filter media. The probability that a particle will come in contact with the surface of the filter media increases as the length of the flow path increases and as the size of the interstitial opening decreases.

When two wetted particles come into contact with each other, they are held together by hydrogen bonding of the water between their surfaces. If one particle is a particle of filter media and the other is a suspended solid, the suspended solid is said to have been adsorbed on the particle of filter media. The probability that the adsorbed solid will be desorbed depends on the balance of forces between the water molecules holding it to the filter media and those tending to pull it away. If the water in the interstices is not moving, the probability of desorption will be low; if it is moving rapidly, the probability will be high. If the contact area between the adsorbed solid and the particle of filter media is small, the probability of desorption will be high; if the contact area is great, the probability will be low.

One way of increasing the contact area is to coat the surface of the filter media particles with a material that will conform to the shape of particles that come into contact with the coating. The materials used for these coatings should be water soluable so they can be easily applied to the filter media. They should form stronger network-like structures on the filter media than water so they will not be washed from the surface of the filter media by the water passing by.

METHOD OF APPROACH

Coatings on filter media can be detected by their effect on the zeta potential of the filter media. A coated particle has a zeta potential that is characteristic of the coating material and not of the filter media itself. The zeta potentials were determined from streaming potential measurements.

Coated filter media were prepared by mixing 5 grams of Johns-Manville Celite 545 with 250 ml of a solution containing the polyelectrolyte to be used in the coating. The diatomite and the polyelectrolyte were mixed for about 15 minutes with a magnetic stirring device. Some additional mixing took place as the filter media was being pumped into the filter. Water containing the residual amounts of the polyelectrolyte were recylced through the cake as it was forming.

The apparatus used for measuring the streaming potentials of the diatomite filter media was a small, pressure filter equipped with electrodes for detecting the electrical potentials generated by filtration[3]. A recording potentiometer was used to measure these streaming potentials.

Zeta potentials were calculated by means of the following equation:

$$\zeta = \frac{4\pi k \mu E}{DP} \quad \frac{1}{R} + \frac{4\lambda}{\phi} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where, ζ is zeta potential,
k is a constant equal to 8.99×10^9 newton·meters^2 per coulomb^2
μ is viscosity,
E is streaming potential,
D is dielectric constant,
P is pressure loss,
R is electrical resistivity,
λ is surface conductance,
ϕ is the mean particle diameter.

The electrical resistivity of the filtrate is measured with a conductivity cell and bridge. The viscosity and dielectric constant are assumed to be the same as for pure water having the same temperature. If surface conductance is neglected, the apparent zeta potential, ζ, is:

$$\zeta = \frac{4\pi k \mu E}{DPR} \quad \ldots\ldots \quad (2)$$

If equation 1 is divided by equation 2 and the terms are rearranged:

$$\frac{1}{\zeta} = \frac{1}{\zeta_o} + \frac{4\lambda R}{\phi \zeta_o} \quad \ldots\ldots \quad (3)$$

Surface conductance and mean particle size are constants. Equation 3 is the equation of a straight line if the reciprocal of the apparent zeta potential is plotted versus the electrical resistivity of the filtrate for a series of tests made on a given filter media. The intercept is the reciprocal of the characteristic zeta potential of the filter media being tested. A typical plot of the data from a series of streaming potential measurements for a coated filter media is shown in figure 1. The electrical resistivity of the water used in the measurement was adjusted from one test to the next by adding small quantities of sodium chloride.

Pressure losses used in calculating zeta potentials were also used for determining the impermeability coefficient[4] of the filter media:

$$K = \frac{P}{QW} \quad \ldots\ldots \quad (4)$$

where, K is the impermeability coefficient,
P is pressure loss,
Q is flow rate per unit area,
W is weight of filter media in the filter cake per unit area.

RESULTS

Two of the polyelectrolytes used in this study produced potentially useful coated filter media. The shape of their adsorption curves (A and B in figure 2) show that equilibrium was reached. These curves were repeatable.

The other polyelectrolyte, C, was unstable, and solutions prepared with this polyelectrolyte did not produce repeatable coatings (C_1, C_4, and C_5 in figure 2).

Coatings prepared with polyelectrolyte A had little effect on the permeability of the supporting filter media (table I). Polyelectrolyte B affected the permeability of the filter media by making it about as impermeable as

Johns-Manville Hyflo Super-Cel. In one of the tests shown in table I, polyelectrolyte C made the diatomite so impermeable that it was worthless in the filtration of water.

The pH of the water filtered affected the zeta potential of filter aid coated by 0.001 gm of polyelectrolyte A to 1 gm of diatomite (figure 3). Changes in the pH of the water used in testing coated filter media were made by adding small amounts of hydrochloric acid to lower the pH and sodium hydroxide to raise the pH.

These results show that a cationic polyelectrolyte may not impart an electropositive coating to diatomite throughout the complete pH range. It is not known at this time whether the filter media coated with polyelectrolyte A will function as well in removing particulate matter from water above a pH of 8.5 as it will below. Research to be published later has shown that commercial grades of diatomite designed to remove only 70 to 85 percent of the coliforms in water will remove nearly 100 percent when coated with polyelectrolyte A.

SUMMARY AND CONCLUSIONS

Some synthetic organic polyelectrolytes will impart an electropositive coating to diatomite which is superior to that of alum in terms of lower pressure losses during filtration. Streaming potential measurements are useful for evaluating the completeness of the coatings produced by these polyelectrolytes. Filter media coated with polyelectrolytes are potentially useful for water filtration in that they will provide more complete removal of turbidity, bacteria, and color colloids with a lower head loss than non-coated diatomite will.

ACKNOWLEDGMENTS

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TABLE I. IMPERMEABILITY COEFFICIENT OF COATED DIATOMITE AS A FUNCTION OF THE WEIGHT PERCENT OF POLYELECTROLYTE USED IN THE COATING.

Coating used	Weight percent	Impermeability coefficient, ft^5 per gpm/lb	
		Beginning of test	End of test
A	0.0152	0.77	0.78
	0.0200	0.74	0.79
	0.0268	0.84	0.84
	0.0268	0.69	0.73
	0.0446	0.72	0.73
	0.0607	0.72	0.72
	0.0802	0.76	0.75
	0.1200	0.79	0.86
	0.1600	0.83	0.80
	0.2000	0.82	0.81
	0.2000	0.81	0.83
	0.4000	0.76	0.78
	0.8920	0.80	0.80
	1.3380	0.76	0.76
B	0.0267	0.88	0.83
	0.0534	1.01	0.92
	0.1330	2.04	1.69
	0.4000	2.92	1.85
	0.8010	3.25	2.82
C_1	0.1980	0.55	0.58
	0.3960	0.79	0.78
	0.5940	0.72	0.71
C_4	0.4000	0.94	0.76
	0.8000	1.51	1.04
C_5	0.0500	0.72	0.75
	0.1000	0.74	0.75
	0.2000	0.74	0.74
	0.2500	0.98	0.85
	0.3000	2.31	1.29
	0.4000	5.37	1.98
	0.6000	9.39	----
	0.8000	9.33	3.71

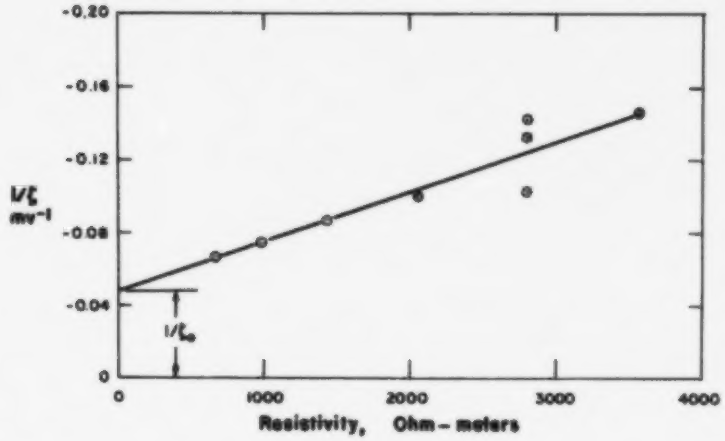


Fig. 1, above. Reciprocal zeta potentials of Celite 545 coated with 1.52×10^{-4} lb. of Polyelectrolyte A per lb. of diatomite.

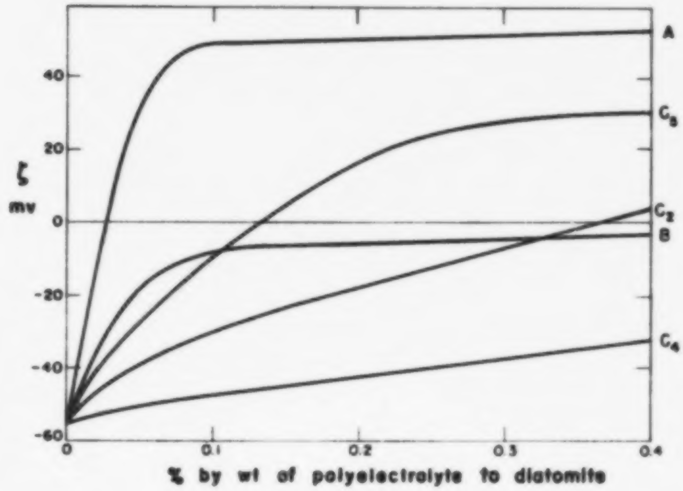
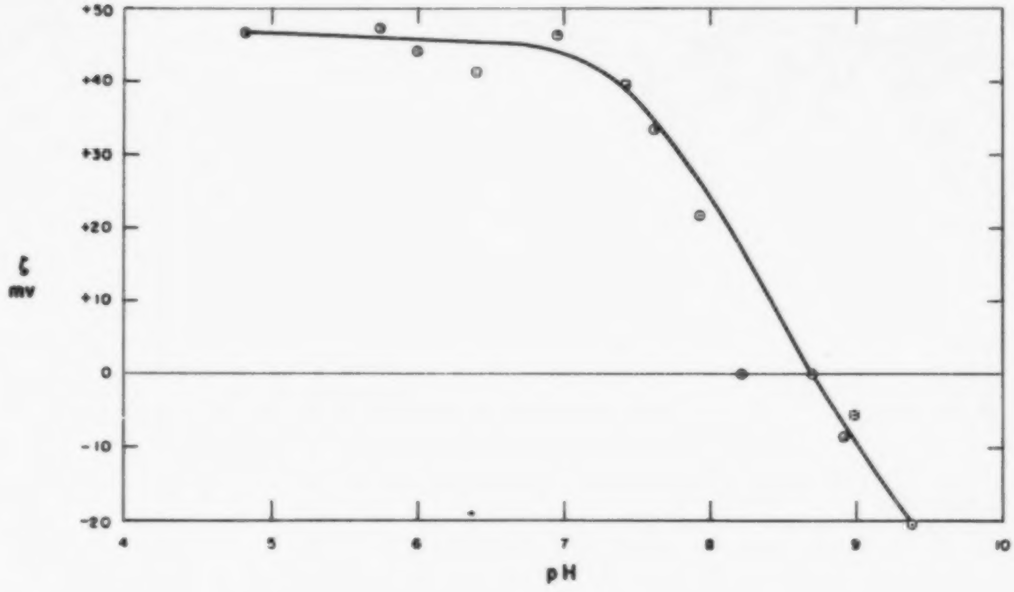


Fig. 2, left. Zeta potential of Celite 545 coated with three different polyelectrolytes.

Fig. 3, below. Zeta potential of Celite 545 coated with 0.1 weight percent of Polyelectrolyte A as function of pH.



PART VI

PERMEABILITY OF FILTER CAKES CONTAINING VARIOUS FLOCCULENT SOLIDS

J. L. Cleasby
E. R. Baumann

Progress Report

PERMEABILITY OF DIATOMITE FILTER CAKES CONTAINING VARIOUS FLOCCULENT SOLIDS

by

John L. Cleasby and
E. Robert Baumann

Project 509-S
April 30, 1964

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PERMEABILITY OF DIATOMITE FILTER CAKES CONTAINING VARIOUS FLOCCULENT SOLIDS

by

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United States Public Health Service
Division of Water Supply and Pollution Control
Research Grant WP-00196

Project 509-S
Municipal Diatomite Filters

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April 30, 1964

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INTRODUCTION

Diatomite filtration of potable water began during World War II, when it became necessary to provide mobile, lightweight filtration equipment which would be more effective than military sand filters. After the war, various types of diatomite filters were applied to civilian purposes. Research and field evaluation have established more adequate design criteria, which have increased the success of diatomite filtration.

Diatomite filter aids are manufactured from diatomaceous earth deposits which consist of siliceous fossil remains of dead diatoms. The engineer must have a knowledge of the hydraulic and filtering characteristics of the filter aid that will be purchased before he can design an adequate, economical filtration plant. An inefficient plant may result from short filtration cycles which will produce a considerable increase in the cost of production; or inefficiency may be due to passage of suspended solids into the effluent from the plant. These difficulties can be reduced in design by the proper specification of diatomite filter aid grades, body feed rates, terminal head losses, and filtration rates.

Diatomite filter aids are commercially available in many different gradations. Even though the median size of the various commercial grades range only from 5 to 30 microns, the degree of clarity of the filter effluent and the permeability of the filter cakes vary considerably. In the design of a filtration plant, the engineer must select the particular grade of diatomite that will give the maximum permeability of the filter cake with satisfactory clarification of the effluent.

The rational design of diatomite filters depends on the predicted head loss development which can be expected when filtering a given water with a selected commercial grade of diatomaceous earth. The necessary equations for head loss prediction have been developed[4]. However, the permeability of diatomite must be known before the equations can be applied. This study is one of a series to be completed to collect permeability information for cakes formed when filtering various types of suspended solid with several commercial filter aids.

LITERATURE REVIEW

In 1957 Phillips[21] summarized current knowledge in the field of diatomite filtration of water. An extensive early study of the application of diatomite filtration for municipal water supplies was made by Sanchis and Merrell[22] in 1951. They investigated the feasibility of using diatomite filters on reservoir supplies for Los Angeles to solve a taste and odor problem caused by algae growth in the storage reservoir. They concluded that diatomite filters produced water equal in both cost and quality to that produced by conventional means and with the advantage of requiring less plant space.

Bell[7] made a direct, full plant scale, economic comparison of sand versus diatomite filtration of a surface water supply. This study indicated a much higher capital investment for sand filters because of the need for a larger plant site and filter building. Diatomite filters involved higher costs of operation and maintenance than did equivalent sand filters. The cost of sand filtration plus pre-treatment was approximately equal to the cost of diatomite filtration of raw water without pre-treatment. Water of acceptable clarity which met bacteriological standards was produced by diatomite filtration, whether raw or pretreated water was used.

Experiences with diatomite filters in municipal installations in New York were reported in 1954[12]. Results of operating four municipal diatomite plants with surface water supplies in New York State were given. Diatomite filter installations with good quality, unpolluted water supplies were found to be practical for small communities with limited capital to invest in a treatment plant.

In 1957, Baumann[3] summarized operating experiences at all municipal diatomite filtration plants then in operation in the United States. A questionnaire was sent to all state health departments to determine current attitudes toward and experiences with municipal diatomite plants. The results indicated a variable willingness on the part of public health regulatory personnel to approve diatomite filtration: at that time 6 states approved, 10 states approved with reservation, 20 did not approve, and 14 states had no set policy on the subject. States indicating reservations generally mentioned that diatomite plants should be used only on unpolluted well supplies and not on surface supplies. Reasons given for objections to diatomite plants were: lack of understanding of the process, lack of enough data in the field, and poor results from the plants previously built. A study was also made of municipal diatomite plants both operating and abandoned. The frequent failure of such plants was believed to be due to poor design and operation because of a lack of knowledge of the basic principles involved.

Current studies of diatomite filtration at Iowa State University began when pressure and vacuum diatomite filter pilot plants were operated to compare their operating characteristics[17]. The advantages and disadvantages of each type of filter were reported as follows. Vacuum filters were easier to operate and easier to check for possible failure of the filter cake. Vacuum filters were less suitable for iron removal because the available terminal head loss was inherently limited to about 20 feet of water, and filter runs were relatively short. In these tests, the water contained some soluble iron which appeared in the effluent during much of the run using vacuum filters. Pressure filters produced longer runs, which yielded more economical filtration. Soluble iron bleed-through occurred during only a very small fraction of the total length of run using the pressure filters.

LaFrenz[14] conducted a large number of filter runs under a wide range of operating conditions. These were used to develop a diatomite filtration equation[4] and a method for economical design of municipal diatomite plants for iron removal[5]. This design is based on the optimum combination of filtration rate, terminal head loss, and body feed to produce potable water at minimum cost. This design method was demonstrated by using it to design diatomite filtration plants for three cities of various sizes[5]. It was concluded that a flow-rate of one gpm/sq ft was optimum for all cities, and a ratio of concentration of iron to concentration of body feed of 0.2 was found to provide maximum economy of filtration. High terminal head losses (50 to 100 feet) and low body feed rates provided lowest filtration costs.

Coogan[9] reported on iron and manganese removal at four municipal installations in Massachusetts. Iron removal was good if the iron was completely oxidized to the ferric state by aeration or with the aid of chlorine or potassium permanganate. Manganese produced much shorter runs than iron if the concentrations in water were the same.

Baumann et al.[4] published a theory of diatomite filtration including an equation for head loss development in diatomite filtration. This equation serves in this study as a basis for comparison of the filtering characteristics of filter cakes containing various suspended solids:

$$H = K_3QW_1 + K_4C_DQ^2t \ (8.33 \times 10^{-6})$$

where:

H = total head loss in filter cake (feet of water)

K_3 and K_4 = constants (min ft^5/lb gal) including the coefficient of permeability of the filter cake and the bulk density of the diatomite in the precoat layer and body feed layer respectively. K_4 was determined experimentally in this study.

Q = flowrate (gal/min ft^2)

W_1 = weight of precoat layer (lb/ft^2)

C_D = concentration of body feed used (mg/l or ppm)

t = time since beginning of filter run (min)

The value of K_3QW_1, which represents the head loss through the precoat layer of the filter cake, remains constant during a filter run and is a function of the diatomite itself. This term is small and relatively insignificant in affecting the total head loss during filtration. The second term, $K_4C_DQ^2t$ (8.33×10^{-6}), represents the head loss through the layer of suspended solids and body feed layer. At the start of a run the head loss through this layer is zero, but it increases throughout the filter run. Head loss during a filter run in feet of water is plotted against total volume of water filtered in gallons per square foot. With body feed in the optimum range, a straight line results. From the slope of this straight line, values of K_4 can be computed since Q, C_D, and t are easily determined.

Baumann et al.[4] indicated that an exponential relationship exists between K_4 and the ratio of suspended solids concentration to body feed concentration. Therefore, a log plot of this data will form a straight line, and the relation for a given water and grade of diatomite can be established by 3 or 4 pilot plant runs.

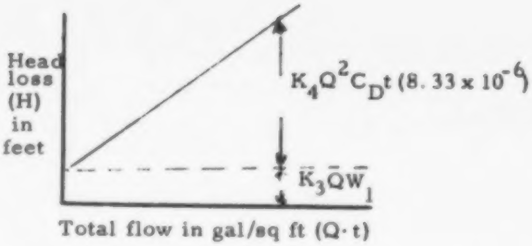

Figure 1. Theoretical plot of filtration equation

The impermeability of precoats consisting of various grades of diatomite was determined in studies by Dillingham[10]. It was reported that there is a difference in the K_3 value for the different grades of diatomite. Also, it was found that the impermeability of the precoat would frequently be different for different manufactured lots of the same grade of diatomite. Since the value of K_3 will be different for each grade of filter aid, the value of K_4 for a body feed-suspended solid filter cake may be expected to be a function of the K_3 value of the filter aid used as body feed.

OBJECTIVES

A pressure diatomite filter pilot plant was operated with synthetic waters containing various suspended solids and various grades of diatomite to determine:

1. The effect of two different methods of introducing body feed into the filter influent on the impermeability of the filter cake (K_4). In one method, dry diatomite was introduced into the influent line of the filter. Precipitation of the suspended solids (iron or aluminium floc) had already occurred before the raw water came into contact with the diatomite. In the other method, the filter aid was fed directly into the raw water preparation tank. This method provided intimate contact be-

tween the filter aid particles and the suspended solids while the floc was forming in the tank. Field experience had indicated that the contact of the floc during formation with the foreign, inert, solid diatomite particles might change the characteristics of the floc and the filter cake. Hem[13] indicated that United States Geological Survey studies have shown a similar effect with manganese, which has characteristics similar to several solids used in this study.

2. The effect of various suspended solids on the impermeability of the filter cake (K_4). The precipitates were prepared by adding various chemicals to tap water. The chemicals studied included: ferrous sulfate ($FeSO_4$), ferric chloride ($FeCl_3$) ferric sulfate ($Fe_2(SO_4)_3$), aluminum sulfate($Al_2(SO_4)_3$), and ferrous chloride ($FeCl_2$).

3. The effect of using different grades of filter aid as body feed on the impermeability of the body feed layer (K_4) when filtering water containing suspended solids prepared with ferrous sulfate.

4. The relation of the impermeability of the body feed layer (K_4) using different grades of diatomite to the impermeability of the clean diatomite (K_3).

5. The effluent clarity obtained through the different grades of diatomite and using the different suspended solids.

6. The possible reasons for any difference in impermeability results observed with various suspended solids.

EQUIPMENT - PILOT PLANT

The pilot plant used in this study (figures 2 and 3) was built in 1958, and the details of its construction and operation are given elsewhere[17]. The apparatus consisted of a water preparation and mixing tank, a body feed system, a precoating system, and a pressure diatomite filter (figure 3). The diatomite filter normally contained 7 filter septums. However, in all runs in this study, only two filter septums were used. The septums are 3 1/2 inch diameter fluted plastic cylinders enclosed inside a perforated plastic cylinder fitted over the corrugations and covered by a tightly fitted sock. The septums each have a filtering area of 1,068 square feet. The ends of the Saran sock are coated with rubberized paint to make them impervious. This helps form a uniform filter cake on the sides of the septums. The filter housing is a cylinder of plexiglass sc that the filter cakes can be observed during a filter run for failure. The filter septums, housing, and piping were cleaned periodically by pouring some dilute sulfuric acid solution into the precoat pot and circulating the solution through the system.

The water to be filtered was prepared in a 36 inch diameter steel tank with a water depth of 32 inches and a capacity of 252 gallons. The water was mechanically mixed by a slow speed mixing paddle and was aerated by a diffuser connected to a compressed air source. The diffuser was of three-eighths inch perforated copper tubing placed around the tank circumference at the bottom of the tank. Tap water entered the tank through a flow control valve* at a constant rate of seven gallons per minute and the excess was wasted through the overflow pipe. The temperature of the water was maintained constant in the mix tank by blending cold and hot water through an automatic mixing valve before passage through the flow control valve.

The body feed diatomite was normally fed into the filter influent line between the water mix tank and the pump supplying pressure for flow through the filter. Filter aid

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*Standard Flow Control 76, Dole Valve Company, Morton Grove, Illinois.

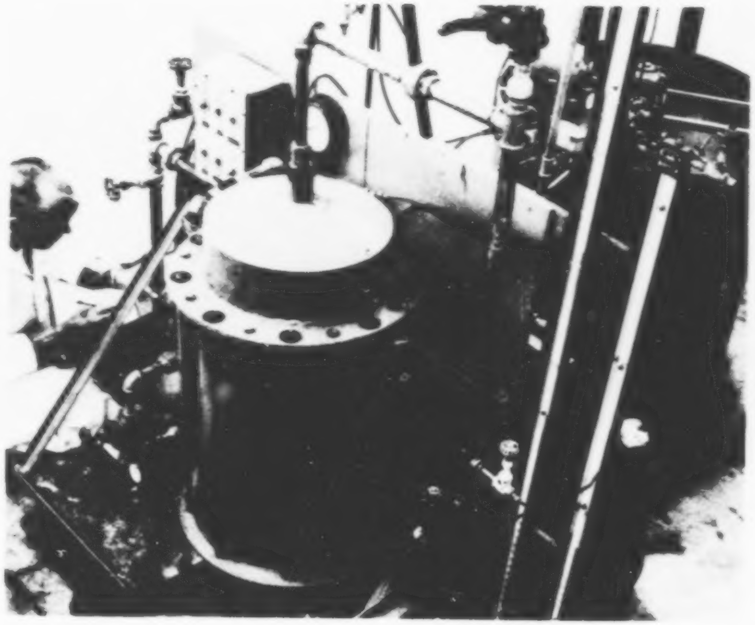

Fig. 2. Pressure diatomite filter pilot plant, mix tank, and body feeder

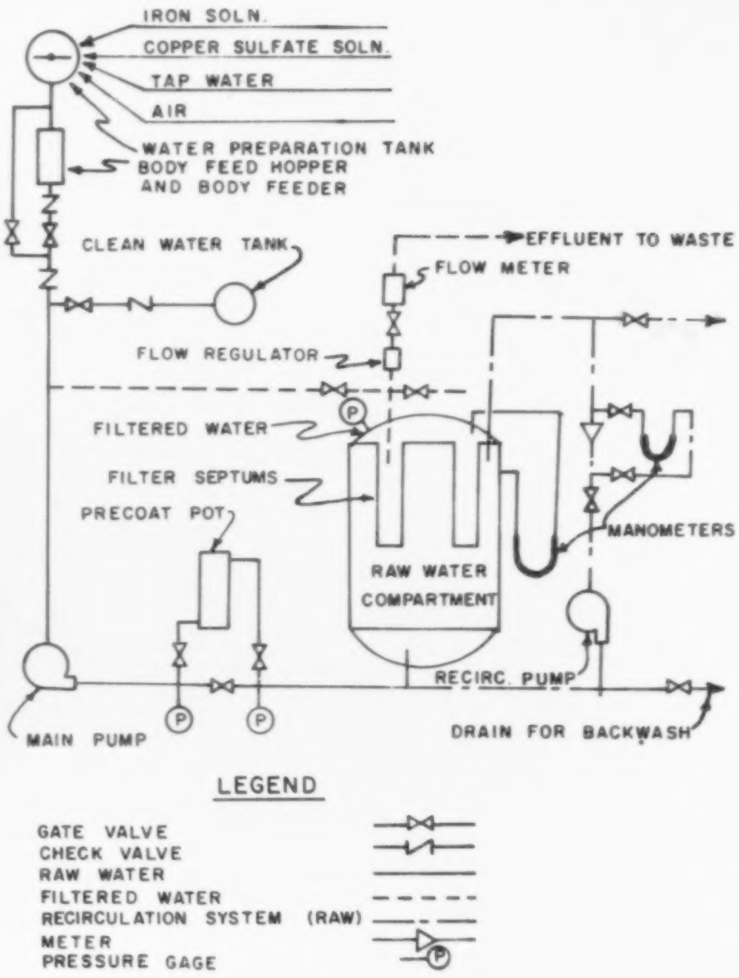

Fig. 3. Schematic drawing of the pilot plant setup.

was fed by a screw type dry feeder[†] into a small hopper type tank which was open at the top. The hopper tank had steeply sloping sides and a retention time of only a few seconds to avoid holding up the diatomite. The filter pump pulled suction from this hopper tank. Samples of unfiltered influent water were taken from the hopper for analysis. The body feed rate was controlled at the feeder by a time clock which allows the feed to run for any pre-selected time between zero and one hundred percent of each minute. The manufacturer recommends using settings in the range of ten to ninety percent for most consistent results. Body feeds could thus be varied from about 50 to 300 mg/l at the flow rate of 1 gpm/sq ft used in all runs.

Several calibration runs were made to determine the body feed rate versus timer setting. Each successive calibration indicated that the feed rates for a given feeder setting were gradually increasing. It was deduced from this that the feeder was degrading the diatomite particles in normal operation in moving the filter aid from the storage hopper to the feed screw. Since very small amounts of diatomite were actually fed, the detention time was long enough that the action of the feeder gradually changed the effective particle size of the diatomite. The degradation increased the dry density of the diatomite. Since the feeder is volumetric, the weight of diatomite fed gradually increased while the volume fed remained nearly constant.

To determine the quantitative amount of degradation which takes place, the particle sizes of a number of samples of filter aid taken from the body feed hopper after various periods of operation were determined as described by Dillingham and Baumann[10]. The results were inconclusive. Therefore, a series of impermeability values (K_3) was determined for the diatomite from the feeder and for diatomite fresh from the undisturbed shipment. The quantitative value of K_3 is a measure of the impermeability of a clean filter aid precoat. It is determined as described by Baumann _et al._[4] using the small K_3 diatomite filter built by Oulman[20]. By varying the flowrate through a filter cake of constant weight, a plot of head loss versus QW, can be made. K_3 may then be calculated from the slope of the resulting straight line, since $h = K_3QW$. The results indicated that a change in the filtering characteristics of the filter aid (as measured by a change in K_3 from about 0.70 to 1.30) was taking place due to the action of the body feeder.

To avoid such degradation as much as possible, the feeder was emptied and the filter aid was wasted after each day of filter operation. To determine more accurately the body feed rate during each run, two ten minute samples were collected before and after each run to determine the actual body feed rate used. With this procedure, it was possible to duplicate results obtained in previous work using ferrous sulfate as the iron source[4].

After leaving the body feeder, the water flows through a high pressure centrifugal pump. In previous work at Iowa State University a slurry type body feeder was used with the inlet located after the pump. Therefore, the diatomite did not pass through the pump in previous runs. However, since previously published data could be reproduced with this new body feed method, no significant degradation of the diatomite particles occurred in the pump nor did this degradation have any significant effect on computed K_4 values.

After the pump, a precoat pot or tank is included in the influent line which can be bypassed after the precoating operation is complete. The raw water then flows into the filter housing and through the septums. The rate of filtration was controlled by a flow regulator* in the effluent line and was measured with a variable area float type meter⁺. A recirculation line was used when precoating the filter to carry water from the filter effluent back to the pump influent. A precoat layer of 0.20 pound of filter aid per square foot was used in all runs. To maintain even filter cake formation a pump was used to recirculate raw water constantly through the housing. This helped to maintain an approximately constant upward velocity in the housing and allowed the filter cake to form evenly. A mercury manometer was used to determine the head loss across the filter cake. A source of clean tap water was available for the precoating operation. In the precoat operation clean water was pumped through the precoat pot containing the desired weight of precoat filter aid and into the filter housing. This clean water was recycled until all of the precoat was deposited on the septums. When the precoat was in place, the influent line from the raw water was opened; the recycle circuit was closed; the effluent valve was opened; the body feeder was turned on; the rate of filtration was set on the flow controller; the precoat pot by-pass line was opened; and filtration proceeded.

[†] B-I-F Volumetric Dry Feeder, Screw type model 25-01, B-I-F Industries, a division of New York Air Brake Company, Providence Rhode Island.

Data recorded included:

1. head loss
2. clock time
3. pH of influent and effluent
4. temperature of influent and effluent
5. total iron or aluminum concentration in influent and effluent
6. soluble iron concentration in the influent.

After the run was completed, the filter was backwashed by an air gurgle type of backwash. Air was allowed to enter the filter housing through the precoat pot as the filter housing drained to break loose the filter cake which then flowed down the drain.

LABORATORY INVESTIGATIONS

Studies have been made at Iowa State University to determine how to make an artificial iron bearing water in the laboratory with filtrability similar to natural iron bearing ground water[15, 23]. All iron bearing waters, both natural and laboratory prepared, must first be aerated to oxidize the iron to the ferric state and sufficient detention time must be allowed to permit flocculation before filtration.

Initially a ferric iron salt was added to University tap water[15]. Comparison of the results obtained with this water with earlier results obtained with the iron bearing raw University water indicated a wide difference in characteristics of filtration between these two type of iron bearing water. La Frenz[14] then added ferrous iron salt to the University tap water. The floc formed upon aeration and subsequent filtration produced filtration characteristics (K_4 of the filter cake) which approximated the results obtained on the aerated University well water. Copper sulfate was also added to aid in the precipitation of the iron in some experiments. Without the copper, some of the iron (0.6-0.7 ppm out of 8.0 ppm) remained in solution. This was true in both the artificial and natural iron-bearing waters.

The University tap water comes from deep wells and is treated for iron removal by aeration, sedimentation, and rapid sand filtration. It is then chlorinated before entering the distribution system. A mineral

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[*] Kates type SA, W. A. Kates Company, Deerfield, Illinois.

[+] Fisher and Porter Flowrator Meter, Figure 1735 Standard Enclosed Meter, Fisher and Porter Company, Hatboro, Pennsylvania.

analysis of University tap water indicated the following[18]:

All results in mg/l	
Total residue	537.00
Alkalinity (as $CaCO_3$)	320.00
Aluminum	0.05
Calcium	114.00
Chloride	11.00
Copper	0.25
Fluoride	0.40
Iron	0.05
Magnesium	61.00
Manganese	0.20
Nitrate	0.70
Phosphate	0.15
Potassium	2.50
Silica	12.00
Sodium	19.50
Sulfate	210.00

The object of this study was to investigate the difference in impermeability (K_4) of filter cakes resulting when various salts were added to University tap water and to attempt to discover the reason for the diference. Furthermore, the effect of using different grades of filter aid as body feed on the impermeability of the resulting cake was studied.

Solutions of each salt to be fed to the water were prepared and stored in 20-liter bottles. Concentrated sulfuric acid was added to aid in keeping the solids in solution in the bottle. The concentrated solution was then fed into the mix tank through a capillary tube along with seven gallons per minute of tap water. The sulfuric acid concentration was approximately 0.35 molar. The salt concentrations in the bottle were 0.50 molar ferrous sulfate, 0.29 molar ferric sulfate, 0.51 molar ferric chloride, 0.70 molar ferrous chloride, and 0.20 molar aluminum sulfate. The feed rate was varied with each solution to give the same desired iron or aluminum concentration in the mix tank, 8mg/l. Copper sulfate solution was fed into the tank in a similar manner to give a concentration of 0.5 mg/l of copper in the water. The water was then aerated by a combination of bubbling compressed air through the water and mechanically mixing the water. The mix tank has a theoretical detention time of 36 minutes at seven gpm. The aeration serves to oxidize the ferrous iron to ferric iron and to form floc particles composed either of a hydrated ferric oxide or of hydrated aluminum oxide.

The filter aids used in all tests were manufactured by the Johns-Manville Corporation. These included the following four commercial filter aids[10]:

Grade	Approximate value of K_3	Mean particle size, microns
Celite 545	0.73	21.0
Celite 535	1.00	16.2
Celite 503	2.08	12.8
Hyflo Super-Cel	3.57	9.5

The water temperature was maintained at 60° F in all tests to rule out any variation in results due to change in water temperature. A thermostatically controlled valve automatically mixed hot and cold water to maintain constant temperature.

Microscopic examination of the various synthetic waters was made with each type of floc. The floc particles were viewed under a magnification of one hundred times in a Sedgwick Rafter Counting Chamber. The microscope was equipped with an ocular micrometer in the eyepiece.

Zeta potential of the floc in the raw water was measured by electrophoretic measurements. Zeta potential is determined by measuring the velocity of migration of the particles in an electric field[20].

Iron concentration in the water was determined by the 2, 2-bipyridine method, a colorimetric method described in Standard Methods[1]. A spectrophotometer was used for the colorimetric tests[*]. This test has been simplified by the Hach Chemical Company, Ames, Iowa, by the use of a patented powder reagent "Biver". This reagent combines the action of the hydrochloric acid solution to dissolve any precipitated iron, the sodium sulfite solution to reduce ferric to ferrous ions, and the bipyridine solution to produce the color complex with the ferrous ions. Tests were made to determine the influent and effluent iron concentration at least once per hour of filter operation.

When a test is made, 25 mg of the "Biver" was added to 25 ml of the sample water. If iron were present, a pink or red solution of variable color intensity which obeys the Beer-Lambert law was produced. The wave length used was 512.5 millimicrons. By using a calibration chart, standardized against iron standard solution as described in Standard Methods[1], the reading of percent transmittancy was converted into total iron concentration in mg/l.

In the runs using ferrous iron salts, tests for soluble iron content were also made. For this purpose the 2, 2-bipyridine test[1] was used. However, the dissolution and reduction of the precipitated iron to the ferrous state was omitted. Samples used for soluble iron were first filtered through Whatman #42 filter paper to prevent any color interference from the rust color of the precipitated iron. For runs using ferric iron salts this method could not be used, because no ferrous iron was present. For these runs filtration and "Biver" powder were used to determine how much iron passed the filter paper. It was found that some iron particles produced from ferrous iron salts were small enough to pass the filter paper. A red color was produced when the "Biver" powder was added to the filtrate. However, the tests using only the bipyridine solution[†] showed that none of this iron which passed the filter paper was still in the soluble ferrous form. In the runs using ferric iron salts, none of the iron passed the filter paper. This indicates that the particles produced from the ferric salts are larger than those produced from ferrous salts. This difference in floc particle size is substantiated by the microscopic examination described previously.

Tests for aluminum concentration made during the series of runs using aluminum sulfate were made exactly as described on page 38 of Standard Methods[2].

A pH meter[‡] which had been standardized against pH 7 and pH 4 buffer solutions was used to determine the pH of the influent and effluent of the filter at least once during each run.

SUMMARY OF RUNS

A complete summary of all of the filtration experiments is presented chronologically in Table I. Runs 1-5, 8, 50, 51, and 52 were trial runs and are void because they were made to become acquainted with the equipment and its subsequent modifications. Runs 13 thru 31 were performed on a subject different from that of this study and are not included in the tabulation. Runs 9-12, and 53-56 used ferrous sulfate as the iron source. Runs 53-56 closely reproduced results obtained in runs made previously[4]. Runs 57 through 63A used ferric chloride, 64 through 70A used ferric sulfate, 71 through 83B

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[*] Beckman Model B Spectrophotometer (Cat. No. 1200) by Beckman Instruments Inc.

[†] Bipyridine Solution B, Hach Chemical Company, Ames, Iowa.

[‡] Beckman Zeromatic pH Meter, Beckman Instruments Inc., Glass Electrodes (Cat. No. 41263).

TABLE I. CHRONOLOGY OF EXPERIMENTAL RUNS

Run No.	Date	Suspended Solids		Inlet point	Body feed		S.S. Concentration / B.F. Concentration	K_4
		Source	Concentration mg/l		Concentration mg/l	Grade*	mg/l / mg/l	Min ft^5 / lb gal
1	3-12-63	$FeSO_4$	6.6	Influent line	254	535	0.026	
2	3-14-63	"	7.2	"	254	"	0.028	
3	3-19-63	"	8.4	"	138	"	0.061	
4	3-21-63	"	7.8	"	138	"	0.057	
5	4- 4-63	"	8.1	"	80	"	0.100	188
6	4- 5-63	"	8.0	"	80	"	0.100	237
7	4- 5-63	"	8.4	"	80	"	0.110	183
8	4- 6-63	"		Mix tank				
9	4-18-63	"	8.1	Influent line	80	"	0.100	185
10	4-18-63	"	8.0	Mix tank	80	"	0.100	195
11	4-19-63	"	8.0	"	80	"	0.100	177
12	4-23-63	"	7.7	"	80	"	0.097	188
32	7- 8-63	"	8.2	Influent line	82	503	0.100	200
33	7-11-63	"	8.0	"	139	"	0.057	52
34	7-15-63	"	8.0	"	284	"	0.028	18
35	7-16-63	"	7.8	"	48	"	0.160	--†
36	7-17-63	"	8.0	"	82	"	0.100	220
37	7-17-63	"	8.1	"	82	"	0.099	227
38	7-19-63	"	8.1	"	87	545	0.093	152
39	7-22-63	"	8.0	"	87	"	0.092	170
40	7-23-63	"	8.1	"	87	"	0.093	157
41	7-24-63	"	8.1	"	146	"	0.055	56
42	7-25-63	"	8.7	"	206	"	0.042	28
43	7-26-63	"	7.9	"	304	"	0.026	12
44	7-30-63	"	8.1	"	84	Hyflo	0.096	238
45	7-31-63	"	7.9	"	84	"	0.094	179
46	8- 1-63	"	7.9	"	84	"	0.094	314
47	8- 2-63	"	7.9	"	84	"	0.094	314
48	8- 5-63	"	7.7	"	124	"	0.062	109
49	8- 6-63	"	7.7	"	205	"	0.038	45
50	5-18-63	"	7.9	"	160	535	0.050	66
51	5-20-63	"	7.9	"	400	"	0.020	16
52	5-21-63	"	7.9	"	50	"	0.160	--†
53	5-28-63	"	7.9	"	170	"	0.047	27
54	5-29-63	"	8.0	"	72	"	0.110	174
55	6- 3-63	"	8.1	"	305	"	0.027	9
56	6- 4-63	"	7.8	"	47	"	0.160	403
57	6- 5-63	$FeCl_3$	7.7	"	73	"	0.110	2170
58	6- 5-63	"	8.0	"	73	"	0.110	2690
59	6- 5-63	"	7.0	"	73	"	0.110	2570
60	6- 6-63	"	8.0	"	154	"	0.052	498
61	6- 6-63	"	8.0	"	328	"	0.024	116
62	6- 7-63	"	8.2	"	51	"	0.160	3040
62A	7- 1-63	"	8.7	"	45	"	0.190	5520
63	6- 7-63	"	8.2	Mix tank	77	"	0.110	1780
63A	7- 1-62	"	8.2	"	73	"	0.110	2420
64	6-10-63	$Fe_2(SO_4)_3$	8.3	Influent line	77	"	0.110	2150
65	6-10-63	"	8.2	"	77	"	0.110	2150
66	6-10-63	"	8.2	"	77	"	0.110	1710
67	6-11-63	"	8.1	"	309	"	0.026	94
68	6-12-63	"	8.0	"	153	"	0.052	442
69	6-12-63	"	8.2	"	55	"	0.150	3580
70	6-13-63	"	8.4	Mix tank	79	"	0.110	1480
70A	7- 2-63	"	7.7	"	75	"	0.100	2010
71	6-26-63	$Al_2(SO_4)_3$		Influent line				
72	6-26-63	"	7.5	"	135	"	0.056	601
73	6-26-63	"	7.5	"	135	"	0.056	593
74	6-26-63	"	7.2	"	135	"	0.053	473
75	6-27-63	"	7.2	"	293	"	0.025	164
76	6-27-63	"	8.1	"	44	"	0.180	3050
77	6-27-63	"	8.2	"	67	"	0.120	
78	6-28-63	"	7.4	"	80	"	0.092	3100
79	6-28-63	"	7.4	"	85	"	0.087	2640
80	6-28-63	"	7.6	Mix tank	75	"	0.110	1610
81	7-10-63	"	8.0	Influent line	48	"	0.170	5040
82	7-10-63	"	7.5	"	147	"	0.051	769

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* Celite grade-Johns Manville Corp.

† Indeterminate

TABLE I. (continued)

Run No.	Date	Suspended Solids Source	Suspended Solids Concentration mg/l	Inlet point	Body feed Concentration mg/l	Grade[*]	$\frac{\text{S.S. Concentration}}{\text{B.F. Concentration}}$ $\frac{\text{mg/l}}{\text{mg/l}}$	K_4 $\frac{\text{Min ft}^5}{\text{lb gal}}$
83	7-10-63	$Al_2(SO_4)_3$	8.1	Influent line	85	535	0.095	2920
83A	8-26-63	"	3.4	"	294	"	0.012	150
83B	8-26-63	"	3.6	"	152	"	0.023	533
84	7-29-63	$FeSO_4$[≠]	7.7	"	75	"	0.100	248
85	8-15-63	"	7.0	"	79	"	0.089	
86	8-15-63	"	7.0	"	79	"	0.089	2020
87	8-15-63	"	7.0	"	79	"	0.089	1810
88	8-15-63	"	8.2	"	290	"	0.028	153
89	8-19-63	"	7.9	"	148	"	0.054	667
90	8-16-63	"	7.7	"	201	"	0.039	324
91	8-26-63	$FeCl_2$	8.1	"	292	"	0.028	10
92	8-27-63	"	7.4	"	211	"	0.035	19
93	8-27-63	"	7.9	"	153	"	0.052	30
94	8-27-63	"	7.3	"	79	"	0.093	109
95	8-27-63	"	8.0	"	83	"	0.097	139
96	8-27-63	"	7.4	"	88	"	0.084	120
97 to 149[#]								
150	8- 8-63	$FeSO_4$	8.2	"	173	Hyflo	0.047	53
151	8- 9-63	"	7.9	"	147	503	0.054	61
152	8-12-63	"	7.9	"	224	"	0.035	38
153	8-13-63	"	7.9	"	124	"	0.064	78
154	8-14-63	"	8.1	"	79	535	0.100	236
155	8-19-63	"	8.4	"	209	Hyflo	0.040	64
156	8-20-63	"	8.2	"	207	"	0.040	52

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[*] Celite grade-Johns Manville Corp.

[≠] Oxidized with $K_2Cr_20_7$

[#] No runs were conducted with these numbers.

used aluminum sulfate, 85 through 90 used ferrous sulfate oxidized with potassium dichromate, and runs 91 through 96 used ferrous chloride. Runs 63 and 77 were discarded because the head loss did not plot as a straight line, and it was impossible to calculate K_4. Run 84 was made with ferrous sulfate with additional sulfate added to increase the sulfate concentration in the water to test the effect of this variable on K_4.

With each series of runs with a particular suspended solids source, the following filter runs were conducted. Three runs were made at approximately 80 mg/l body feed to demonstrate the reproducibility of results. Three runs were made at different body feed rates. One run was made at 80 mg/l body feed with the diatomite being fed into the mix tank instead of into the small hopper in the influent line.

Runs made to evaluate the effect of the grade of diatomite used as body feed on the permeability of cakes produced when using ferrous sulfate as an iron source are: Celite 545, runs 38-43; Celite 535, runs 6, 7, 9, and 53 thru 56; Celite 503, runs 32-37, 151-153; Hyflo Super-Cel, runs 44-49, 150, 155, 156.

TEST RESULTS

DEMONSTRATION OF REPRODUCIBILITY

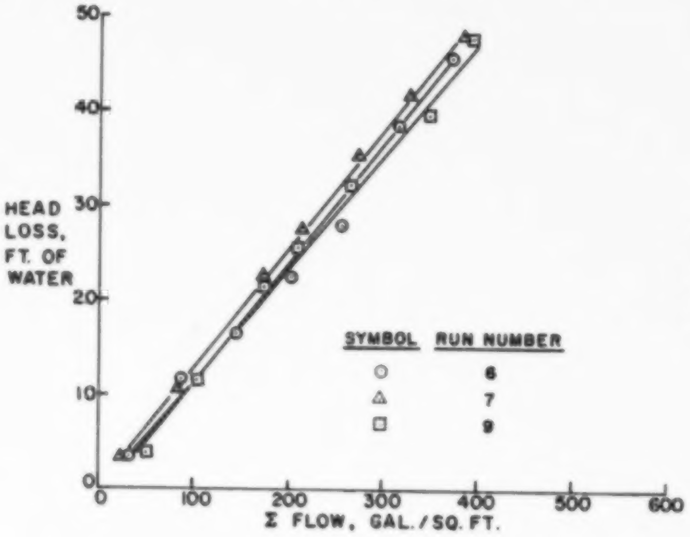
K_4 values were computed at a constant ratio of suspended solids to body feed concentration to show variations due to experimental error. At least three runs were made with each suspended solid, and with each diatomite grade for one ratio of suspended solids to body feed concentration. The reproducibility, as measured by the slope of the head loss vs volume of filtrate curve or by K_4, was generally good, as is shown by the typical data for ferrous sulfate and Celite 535 (figure 4, and table I). The range of K_4 values for a given solid and diatomite grade was very small when compared with the changes that occurred when different suspended solids, different diatomite grades, or different body feed rates were used. Data collected when using Celite 503 and Hyflo Super-Cel was less reproducible than that for the other diatomite grades, as can be seen from the tabulated K_4 values.

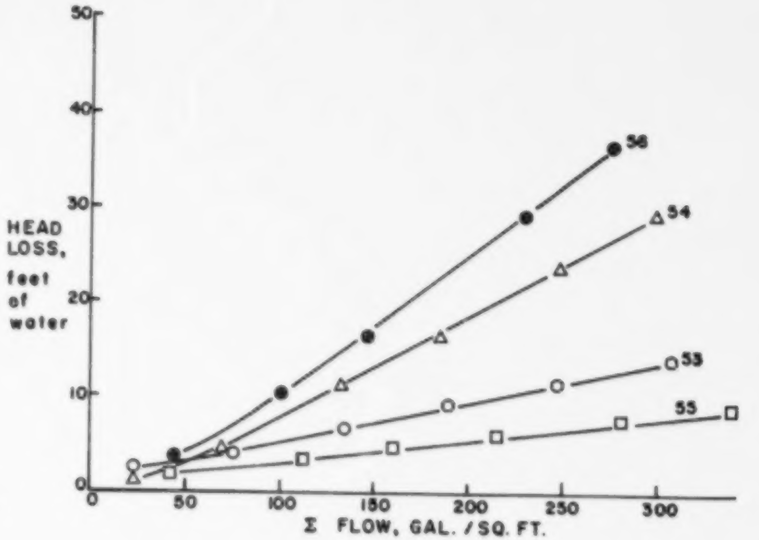
EFFECT OF METHOD OF BODY FEED

The effect of adding the body feed with the iron chemicals in the mix tank was compared with the normal body feed procedure of adding the body feed after the mix tank for several of the sources of suspended solids. Runs for this purpose were made using ferrous sulfate, ferric sulfate, ferric chloride, and aluminum sulfate. The runs made did not show in the head loss curve any significant difference due to these two methods of feeding the body feed.

EFFECT OF VARYING CHEMICAL SOURCE OF SUSPENDED SOLIDS

Figures 5 through 9 indicate a significant difference in the head loss build-up in the diatomite filter between waters using different chemical salts as a source of suspended solids. Water prepared from the trivalent sources of iron (ferric chloride and ferric sulfate) had a very rapid head loss build-up and thus very short filter runs. Water prepared from bivalent salts of iron (ferrous sulfate and ferrous chloride) produced a flatter head loss curve and longer filter runs. These runs closely reproduce runs previously reported by Baumann et al.[4] using ferrous sulfate. K_4 values as computed by the filtration equation were approximately ten times as great for suspended solids from the trivalent sources of iron as from the bivalent sources





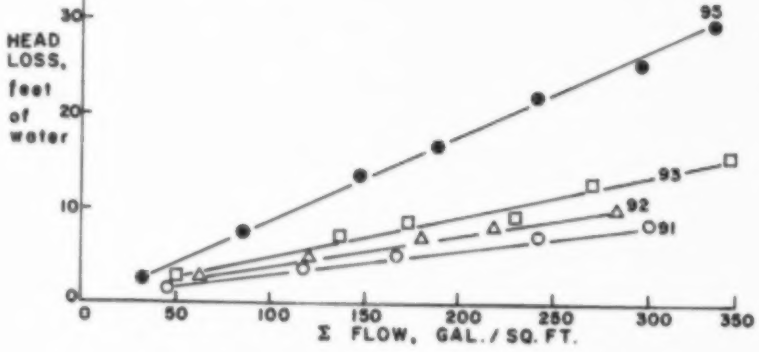


Fig. 4, left, above. Reproducibility of head loss vs volume of filtrate curve

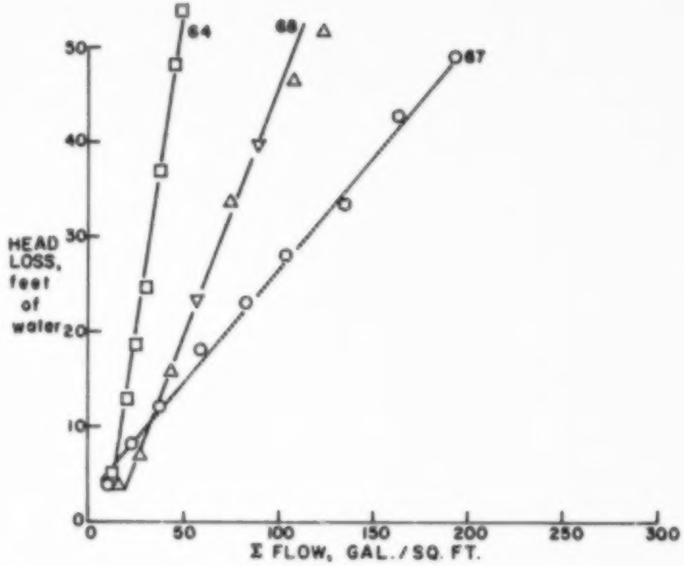
	Run Number	Body Feed (ppm)	Iron Conc. (ppm)
Celite 535	6	80	8.0
Iron source - Ferrous	7	80	8.4
- Sulfate	9	80	8.1

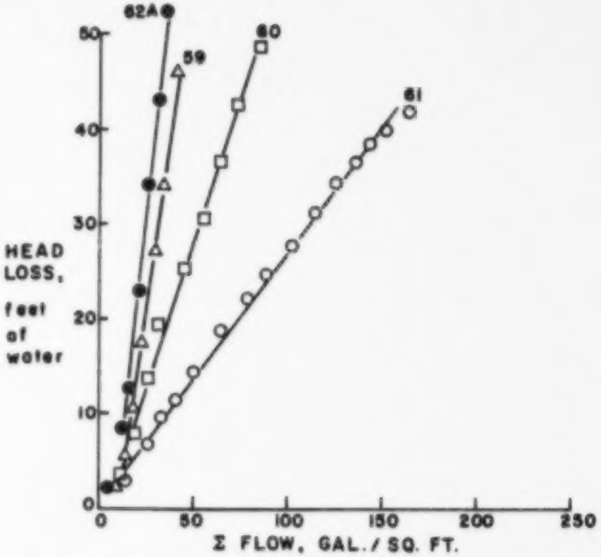
Fig. 5, above. Head loss vs filtrate volume
Iron concentration = 7-8 mg/l
Iron source = ferrous sulfate

Run Number	Body feed concentration (mg/l)
53	170
54	73
55	305
56	48

Fig. 6. left. Head loss vs filtrate volume
Iron concentration = 7-8 mg/l
Iron source = ferrous chloride

Run Number	Body feed concentration (mg/l)
91	292
92	211
93	153
95	83





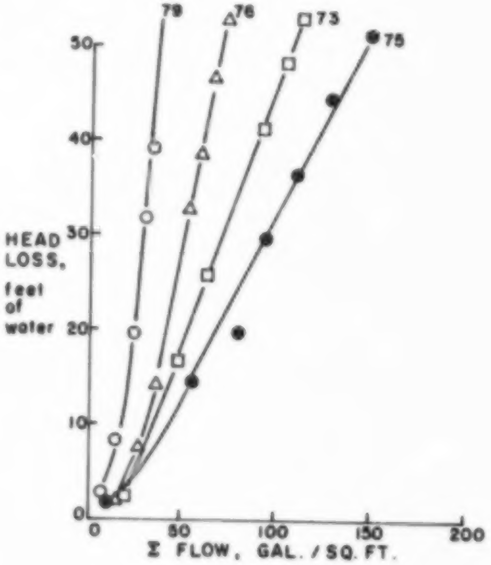


Fig. 7, left, above. Head loss vs filtrate volume
Iron concentration = 7-8 mg/l
Iron source = ferric sulfate

Run Number	Body feed concentration (mg/l)
64	77
67	309
68	153

Fig. 8, above. Head loss vs filtrate volume
Iron concentration = 7-8 mg/l
Iron source = ferric chloride

Run Number	Body feed concentration (mg/l)
59	73
60	154
61	328
62A	45

Fig. 9, left. Head loss vs filtrate volume
Aluminum concentration = 7-8 mg/l
Aluminum source = aluminum sulfate

Run Number	Body feed concentration (mg/l)
73	135
75	293
76	44
79	85

(figure 10). Aluminum sulfate produces head loss curves and K_4 values similar to the ferric iron salts (figures 9 and 11).

Correlation coefficients were calculated for all the curves shown in figures 10 and 11 (table II). The correlation coefficient, a measure of how closely the points on a plot fit the straight line, indicates whether there is reason to believe a straight line relation exists between the two factors. Correlation coefficients vary from +1 to -1. Values close to either extreme indicate good correlation. The sign indicates the direction of slope. Values approaching zero indicate no correlation.

TABLE II. CORRELATION COEFFICIENTS OF CURVES OF K_4 VS RATIO OF SUSPENDED SOLIDS TO BODY FEED CONCENTRATION.

Suspended solid source	Correlation coefficient
Ferrous sulfate	+1.000-
Ferrous chloride	+0.983
Ferric chloride	+0.990
Ferric sulfate	+0.998
Aluminum sulfate	+0.926
Ferrous sulfate oxidized with potassium dichromate	+0.998

The results of the microscopic examination of floc size in the raw water are summarized in table III. These results indicate larger floc particles were formed with the ferric iron salts than with ferrous iron salts. The larger floc particles and the filter aid particles are comparable in size and may totally fill the spaces between the filter aid particles in the cake, thus obstructing the flow. The smaller floc particles are small enough that several floc particles may coat a diatomite particle leaving space for the water to flow through more easily. This could explain the variation in head loss build-up with the two forms of iron.

An attempt was made to find the reason for the significant differences in floc size. The first hypothesis tested was that the sulfate or chloride anion concentration was responsible for this size difference. The results from previous work[14, 17] were plotted along with some of the data from this investigation (figure 12). LaFrenz used artificial iron bearing water with ferrous sulfate as the iron source solution[14]. Miley used iron bearing, aerated University well water[17]. This plot indicated a possible relation between K_4 values of filter cakes containing iron and sulfate concentration.

The attempt to verify this hypothesis failed. Sulfate concentrations in the raw water resulting from the use of ferrous sulfate and ferric sulfate sources were computed. Enough sulfuric acid was added to the bottle of ferrous sulfate solution to make the sulfate concentration in the raw water equal to the concentration in the ferric sulfate runs. The results indicated that no significant change in the head loss curve occurred due to the addition of sulfate.

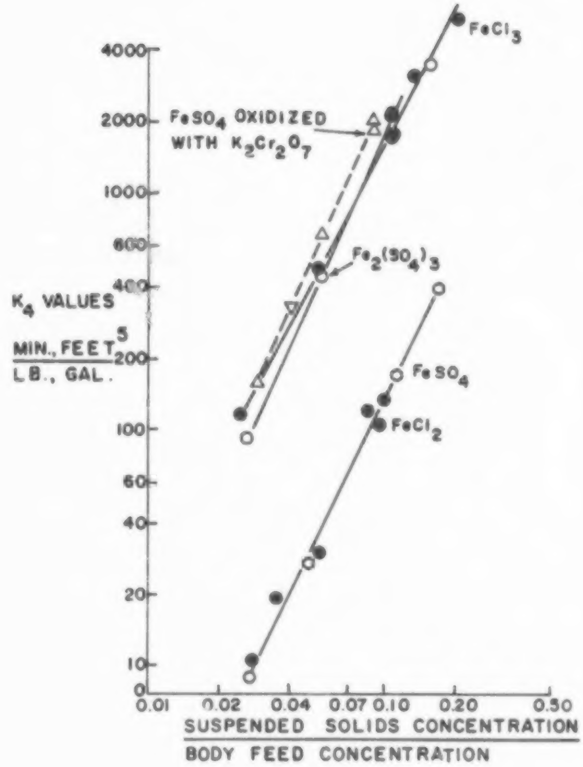
TABLE III. FLOC PARTICLE SIZE

Suspended solids source	Largest (microns)	Mean	Smallest
Ferric chloride	105	33	6
Ferric sulfate	95	38	9
Ferrous sulfate oxidized with potassium dichromate	47	26	10
Ferrous sulfate	25	6	4
Ferrous chloride	25	19	5
Aluminum sulfate	Floc particles were transparent and particle size could not be measured.		

Zeta potentials of the various flocs were measured by electrophoresis. These results are shown in table IV. There is no apparent relation between floc zeta potential and the K_4 values obtained with the suspended solids from the various chemical sources.

TABLE IV. ZETA POTENTIAL OF FLOC PARTICLES

Suspended solids source	Zeta potential (millivolts)
Ferrous sulfate	-23.54
Ferric chloride	-21.32
Ferric sulfate	-18.70
Aluminum sulfate	-24.60
Ferrous chloride	-18.10



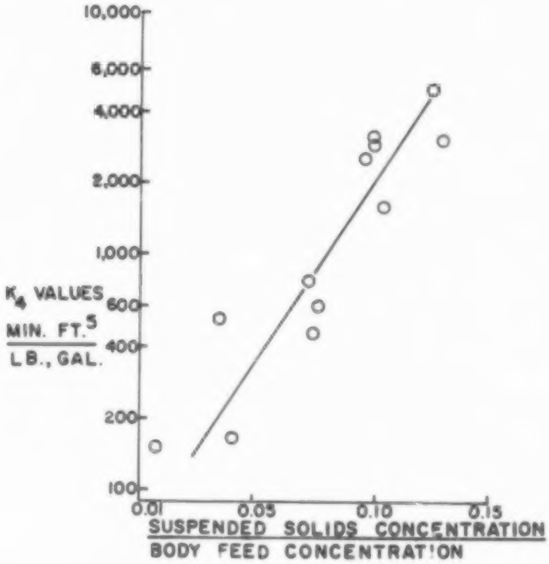
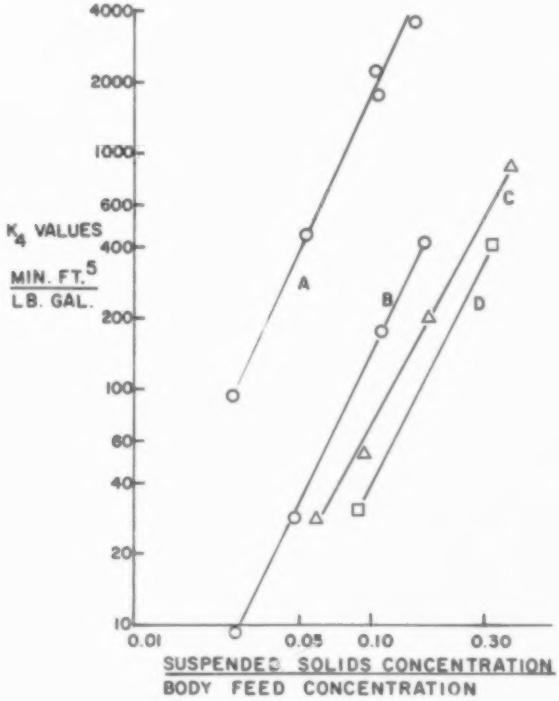


Fig. 10, above. Relation of impermeability (K_4) to ratio of suspended solids to body feed concentration for solids prepared from different iron salts.

Fig. 11, right, above. Relation of impermeability (K_4) to ratio of suspended solids to body feed concentration for solids prepared from aluminum sulfate.

Fig. 12, right. Comparison of current data with previous data to show the possible effect of sulfate on cake impermeability (K_4).

	Suspended Solids Source	Sulfate Concentration (mg/l)	Investigator
A	Ferric sulfate	158.4	Hawley
B	Ferrous sulfate	148.0	Hawley
C	Ferrous sulfate	138.5	La Frenz[a]
D	University well water	124.0	Miley



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[a] No sulfuric acid [illegible] to iron source solution.

Next, it was hypothesized that the oxidation state of the cation in some way affected floc size in the raw water. The ferric chloride and ferric sulfate were found to precipitate in the chemical bottle. The precipitate is in the form of small size particles which do not settle even if the bottle is allowed to stand for days, as it was before these runs. A single eighteen liter bottle would last through three or four days of filtration. However, the floc particles are clearly visible by the Tyndall effect when a narrow beam of light is directed through the chemical feed solution near its surface. If a sample of the ferrous iron solution is viewed in this manner, fewer and smaller particles are visible in the beam of light. Apparently, the oxidation to the ferric state is also responsible for the change in color of the feed solution from the light green of ferrous salts to the dark brown or black of ferric salts.

To test this theory, a regular eighteen liter bottle of ferrous sulfate solution was completely oxidized to the ferric form by the use of a slight excess of potassium dichromate. The solution turned the characteristic dark color of the ferric iron. The color was even blacker than the other ferric chemicals used. When a beam of light was directed through the solution-suspension, small particles similar to those of the ferric iron suspensions were seen. The results of a series of runs using this oxidized ferrous sulfate is shown in figure 12. The plot of K_4 vs ratio of suspended solids to body feed concentration is included in figure 10.

These results indicate that it is the oxidation state of the cation which is primarily responsible for the formation of the colloidal size particles in suspension in the chemical bottles. These particles when fed into the mix tank form larger floc particles. It is hypothesized that the larger floc particles clog the spaces between diatomite particles in the filter cake and serve to increase the rate of head loss build-up greatly in a diatomite filter. To improve filtration of such flocculent solids, the size of the floc should be kept small as compared with the size of the filter aid particles.

EFFLUENT QUALITY

The amounts of iron remaining in the effluent samples from the filters were not appreciably different when different suspended solids or grades of diatomite were used. Maximum concentrations of iron or aluminum found in the effluent were 0.3 ppm for all of the diatomite grades studied.

EFFECT OF GRADE OF DIATOMITE ON CAKE PERMEABILITY

The manufacturers of diatomite filter aids have placed on the market many different grades of diatomite. These grades vary from coarse gradations to very fine gradations. What actually is the hydraulic difference in filtering characteristics between a coarse grade and a fine grade? Does the increase in coarseness sacrifice the quality of the effluent? Will the increase in length of run obtained by the coarser grades of diatomite justify economically the increased cost of the coarser grades of filter aid?

The value of K_3 is a measure of both the fineness and hydraulic characteristics of clean diatomite[10]. K_3 is related to the reciprocal of the coefficient of permeability of the precoat . Permeability is a measure of the ability of a porous media such as diatomite to transmit water under the influence of a pressure differential. The coefficient of permeability is the rate of flow per unit of cross-sectional area under a hydraulic gradient of unity at standard temperature. The value of K_3 may be determined by passing previously filtered water through the precoat and measuring the head loss at various filtration rates.

Previous studies have presented data for the K_3 value of various grades of diatomite[10]. It was found that each grade of diatomite has different K_3 value. Since the K_3 value varies between different grades of diatomite, it was expected that for a specific suspended solid, there would be a different K_4 value for each grade of diatomite used as precoat and body feed.

A series of filter runs was conducted to evaluate the effect of the grade of diatomite used as body feed upon the resulting cake permeability. The head loss development observed in these filter runs using various grades of diatomite for filtering an iron floc suspension prepared from ferrous sulfate are presented in figures 14 through 17. The relation between K_4 values and the ratio of suspended solid to body feed concentration for the same filter runs is shown in figures 18 through 21.

A summary of the relationships between K_4 vs ratio of iron concentration to body feed concentration for the four grades of filter aid studied is shown in figure 22. The value of K_4 for a given ratio of the iron concentration to body feed concentration is higher as the grade of diatomite becomes finer and its value of K_3 increases. However, the K_4 values obtained with Celite 545 are higher than with Celite 535. Celite 545 is normally coarser than Celite 535.

The reason the results differ so greatly from those to be expected may be explained by considering the K_3 values for each of these grades[10]. The average K_3 value for Celite 535 is 1.00 $\frac{(\text{min})\ (\text{ft}^5)}{(\text{lb})\ (\text{gal})}$ and for Celite 545, 0.73.

However, the K_3 values for the particular lots of Celite 535 and Celite 545 used in this study showed that the K_3 value for Celite 535 in this study was 0.74 and the K_3 value for Celite 545 was 0.76. The K_3 value for Celite 545 agrees quite closely with normal lots of Celite 545. However, the K_3 value for the Celite 535 in this study was 25% less than the average of usual shipments. The data for Celite 535 did not fit the data obtained for the other three diatomite grades studied.

As can be seen in figure 23, the percentage of change in the impermeability of the body feed layer (K_4) was not as great as the percentage of change in the impermeability of the precoat (K_3). With an increase of 450 percent in the value of K_3, the value of K_4 increased 48 percent at a suspended solids-to-body feed ratio of 0.09. When this ratio was 0.07, K_4 increased 55 percent as compared with the increase of 450 percent in K_3. Since head loss development is a linear function of K_4, the 48% increase would represent about a 33 percent decrease in run length for a given terminal head loss. Run length is one of the dominant factors affecting labor cost in diatomite filter plant operation. The use of the coarse permeable grades such as Celite 545 could represent a substantial labor savings. The current price of the coarse Celite 545 is only 12 percent more than the price of fine Hyflo Super-Cel. Thus, for 12 percent more cost, a 33 percent increase in run length can be obtained with the suspended solids used in these tests.

SUMMARY

Many natural iron bearing ground waters exist. The various waters exhibit different filtering characteristics in a diatomite filter. This work shows some possible reasons for these differences. These data may be helpful in deciding if diatomite filtration is applicable to a natural iron bearing water. These data also have proved that the theory of diatomite

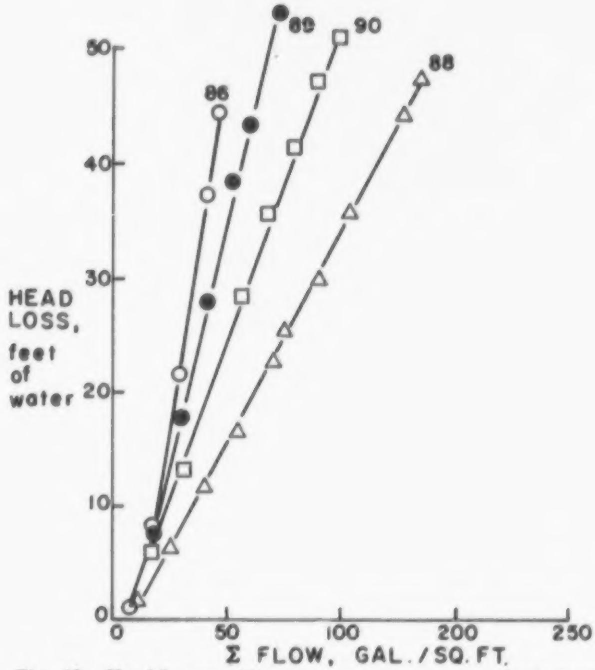


Fig. 13. Head loss vs filtrate volume
Iron concentration = 7-8 mg/l
Iron source = ferrous sulfate
oxidized with potassium dichromate

Run Number	Body feed concentration (mg/l)
86	79
88	290
89	148
90	201

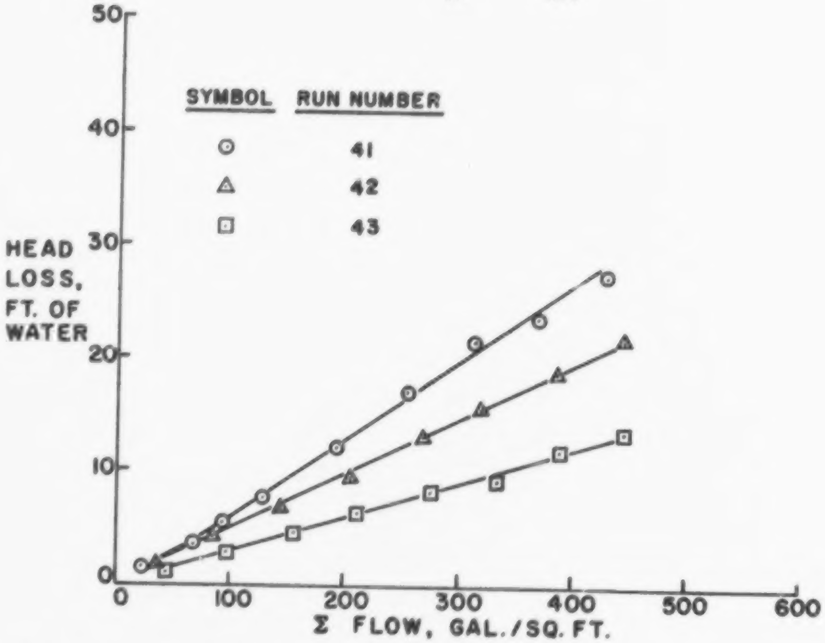
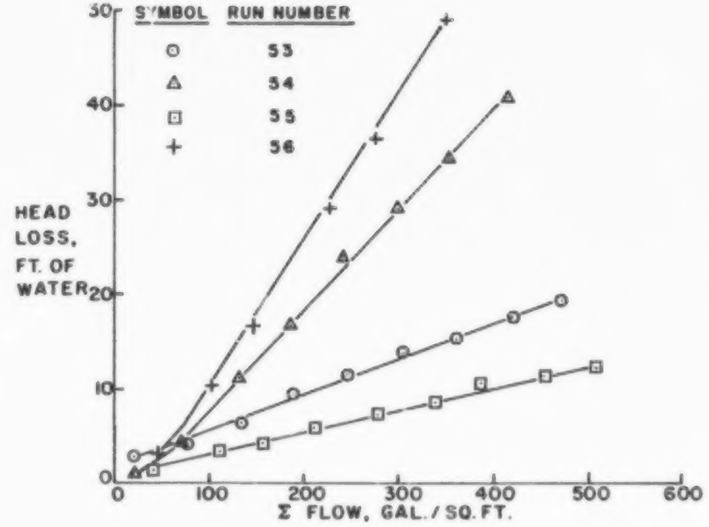
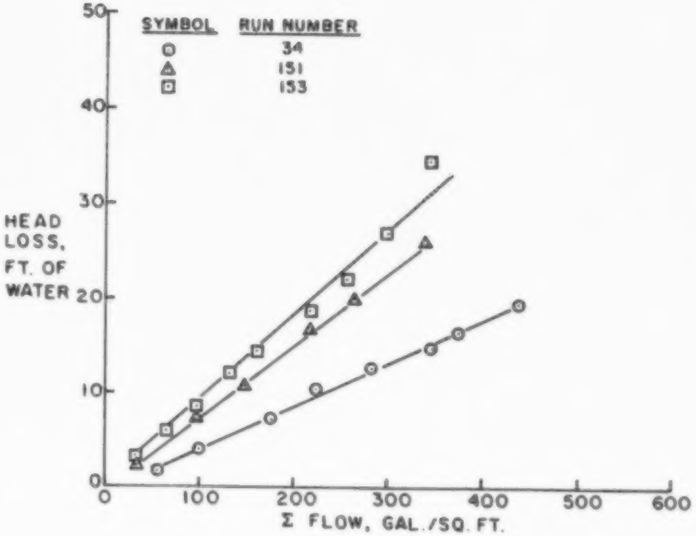


Fig. 14. Head loss vs volume of filtrate using ferrous sulfate and Celite 545.

Run Number	Body Feed (ppm)	Iron Conc. (ppm)
41	146	8.1
42	206	8.7
43	304	7.9





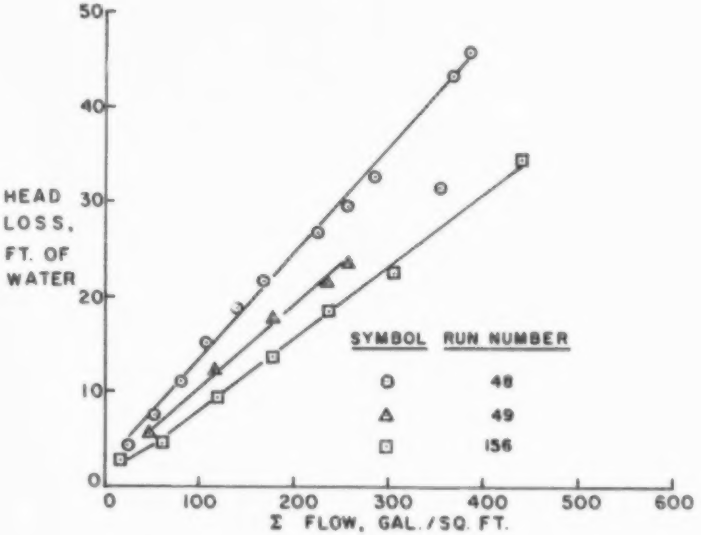


Fig. 15, left, above. Head loss vs volume of filtrate using ferrous sulfate and Celite 535

Run Number	Body Feed (ppm)	Iron Conc. (ppm)
53	170	8.0
54	73	8.0
55	305	8.1
56	48	7.8

Fig. 16, above. Head loss vs volume of filtrate using ferrous sulfate and Celite 503

Run Number	Body Feed (ppm)	Iron Conc. (ppm)
34	284	8.0
151	147	7.9
153	124	7.9

Fig. 17, left. Head loss vs volume of filtrate using ferrous sulfate and Hyflo Super-cel

Run Number	Body Feed (ppm)	Iron Conc. (ppm)
48	124	7.7
49	205	7.7
156	207	8.2

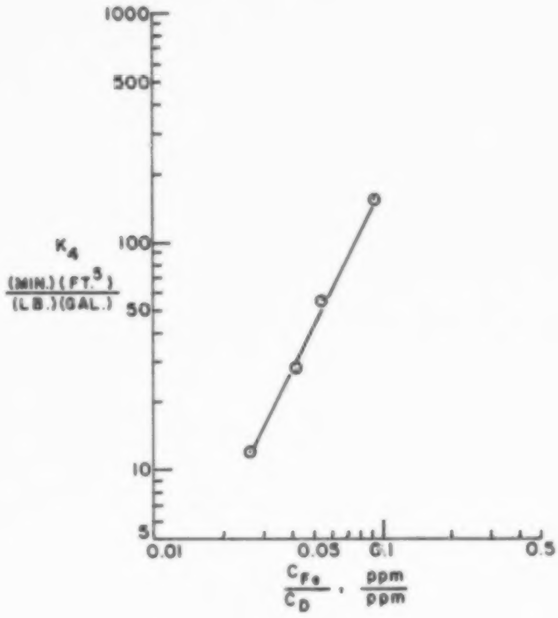


Fig. 18. Relation of impermeability (K_4) to C_{Fe}/C_D for filtering ferrous sulfate floc using Celite 545.

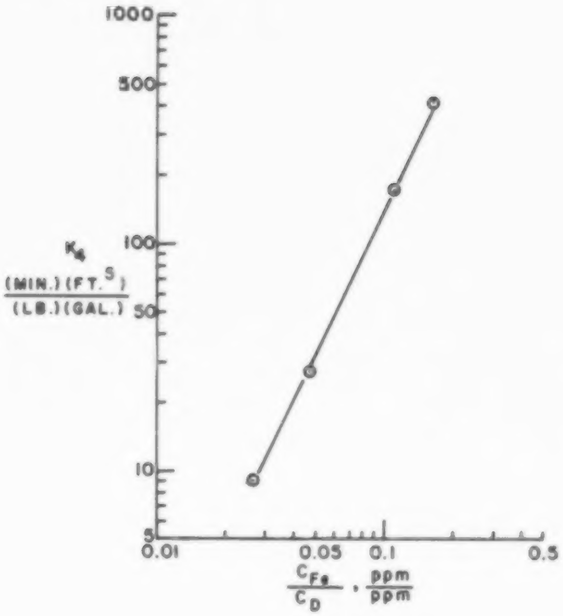


Fig. 19. Relation of impermeability (K_4) to C_{Fe}/C_D for filtering ferrous sulfate floc using Celite 535.

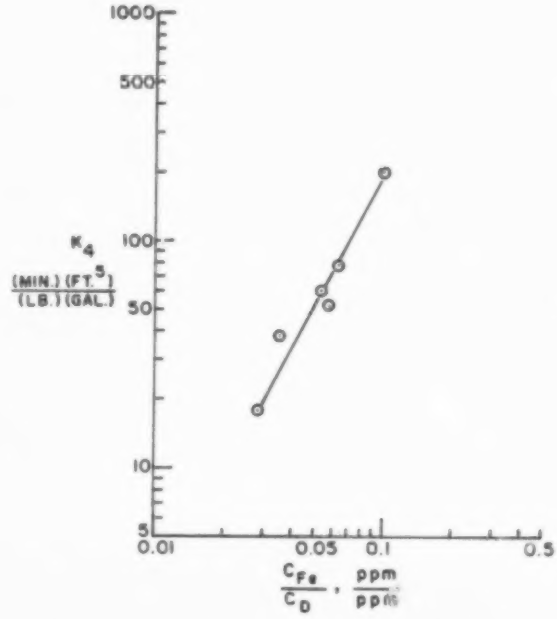


Fig. 20. Relation of impermeability (K_4) to C_{Fe}/C_D for filtering ferrous sulfate floc using Celite 503.

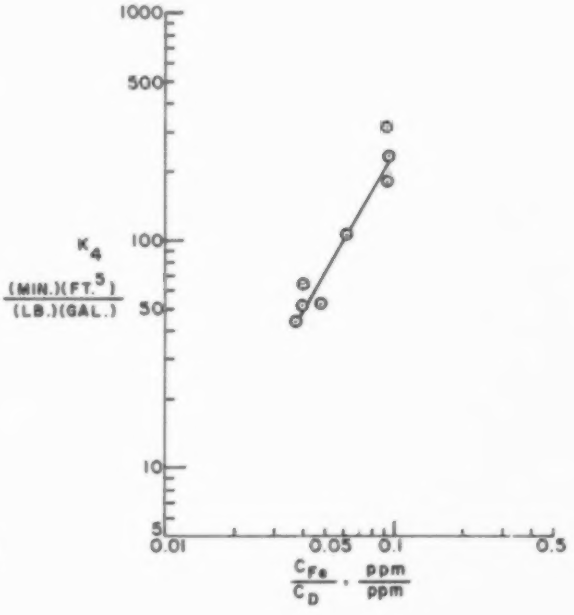


Fig. 21. Relation of impermeability (K_4) to C_{Fe}/C_D for filtering ferrous sulfate floc using Hyflo Super-cel.

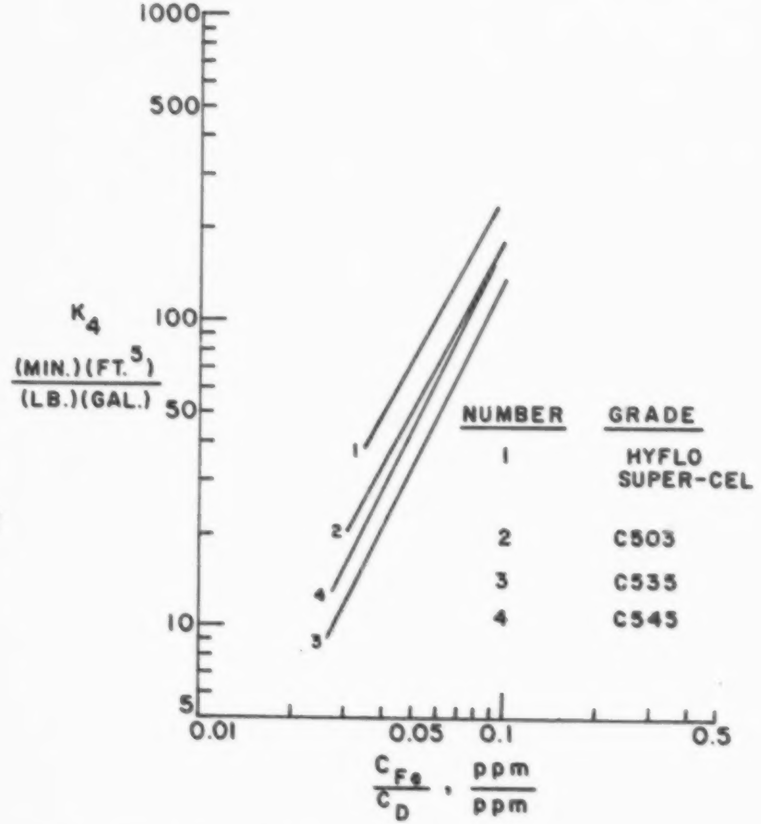


Fig. 22. Effect of grade of diatomite on the relationship of K_4 to C_{Fe}/C_D with ferrous sulfate prepared water.

Grade	K_3 $\frac{(min)}{(lb)}\frac{(ft^5)}{(gal)}$
Hyflo Super-Cel	4.11
C503	1.47
C535	0.74
C545	0.76

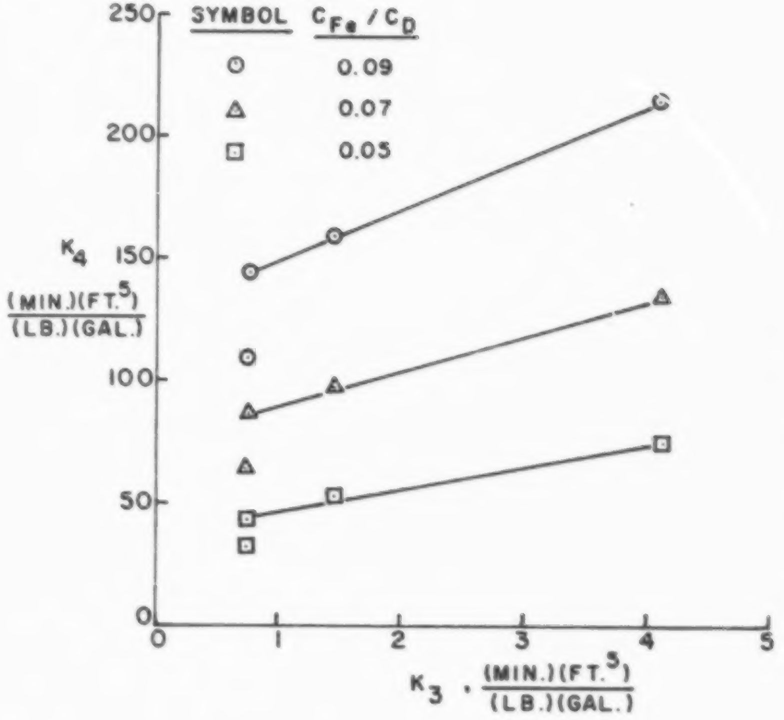


Fig. 23. Effect of K_3 on the value of K_4 with ferrous sulfate prepared water at several ratios of C_{Fe}/C_D.

filtration applies to iron bearing waters from several different chemical sources and also aluminum bearing waters at a flowrate of one gallon per minute per square foot.

A pilot pressure diatomite filter was operated on laboratory prepared synthetic water to determine the effect of three variables on the permeability of the resulting filter cake.

1. Two different body feed techniques were studied to determine the effect on cake permeability and effluent quality. One technique involved feeding diatomite into the raw water tank while the suspended floc was forming. The other involved feeding body feed into the filter influent line after the floc particles had formed.

2. Several different salts of iron and aluminum were used to prepare flocculent solids to be filtered to determine the effect of different suspended solids on both cake permeability and effluent quality.

3. Several different commercial grades of diatomaceous earth were used as filter aids when a single type of flocculent solid was filtered to determine the effect of diatomite grade on cake permeability and effluent quality.

A measure of filter cake impermeability was obtained by calculating K_4 values from the equation of diatomite filtration[4]. A series of at least seven runs was made with suspended solids obtained from five different chemicals: ferrous sulfate, ferrous chloride, ferric chloride, ferric sulfate, and aluminum sulfate. For each salt at least three runs were conducted using both the second body feed method and a single body feed rate to demonstrate reproducibility of the data; one run was made using the first body feed method described above, and three runs were made at various other body feed rates. Microscopic examination and zeta potential measurements of the suspended solids were made.

Many different grades of diatomite are marketed by various manufacturers. The difference in mean pore size between grades influences both the impermeability of the filter cake and the clarity of the filter effluent. The filter aids used in this study were Celite 545, Celite 535, Celite 503, and Hyflo Super-Cel. For each grade, a minimum of six filter runs were conducted to obtain data about the relationship between head loss through the filter cake and the volume of filtrate. The factor that was varied between runs with each grade was the rate of body feed. The rate of filtration, precoat quantity, suspended solid concentration, copper concentration, water source, raw water temperature, and raw water pH were essentially constant during all filter runs.

CONCLUSIONS

As a result of this study, the following conclusions may be drawn:

1. No difference in the filter cake permeability caused by the two different body feed techniques was apparent regardless of the source of the suspended solids.

2. Significant difference in filter cake permeability was discovered for water containing suspended solids from different chemical sources. Impermeability values (K_4) obtained for raw water containing suspended solids from trivalent iron and aluminum salts were approximately ten times as great as the K_4 values for cakes containing solids resulting from use of the bivalant iron salts.

3. Microscopic examination of the flocculent solids showed that the particle size of floc from trivalent iron salts was considerably larger than the particle size of floc from bivalent iron salts. The larger particles were approximately the size of filter aid particles.

4. Examination of the chemical solution used to prepare the artificial raw water showed that the trivalent salts precipitate and form minute particles in the chemical bottle. The particles are presumed to be colloidal, since they do not settle in the bottle; the bivalent salts precipitate much less noticeably in the bottle. This precipitation may contribute to the formation of the larger floc particles in the raw water.

5. When the solution of the bivalent salts was oxidized to the trivalent state, the K_4 values obtained were close to the values obtained with the trivalent iron salts. The oxidation state of the cation is in some way responsible for the floc particle size in the raw water.

6. The grade of diatomite used as body feed affects the impermeability of the resulting filter cake. At the same body feed rate, the finer grades of diatomite produce a filter cake with a slightly higher impermeability value (K_4) in the filtration of a flocculent solid (figures 22 and 23).

7. The percentage of change in the impermeability of the body feed layer (K_4) was not as great as the corresponding percentage of change in impermeability of the clean diatomite (K_3). For example, an increase of 450 percent in K_3 resulted in an increase of 48 percent in K_4 when the suspended solids-to-body feed ratio was 0.09. When this ratio was 0.07, the corresponding increase in K_4 was only 55 percent (figure 23).

However, these changes in K_4 represent major changes in the length of filter run terminated at any given total head loss. The relatively coarse Celite 545 would produce a run length about 33 percent longer than the fine Hyflo Super-Cel for this water. This benefit can be obtained for 12 percent increase in diatomite cost at current prices.

8. The exponential relationship between the impermeability (K_4) and the ratio of the concentration of suspended solid to concentration of body feed was demonstrated for all of the grades of diatomite studied and for all of the different suspended flocculent solids. In the general exponential equation, $K_4 = ax^b$, where "x" is the ratio of concentration of suspended solid to concentration of body feed, exponent "b" was approximately 2 for all the grades and solids studied.

9. There was no appreciable change in effluent clarity between the coarser and finer grades of diatomite or for the various flocculent solids filtered. Effluent iron or aluminum concentrations did not exceed 0.3 ppm in any of the filter runs.

RECOMMENDATIONS

1. Some runs should be repeated using higher filtration rates to find the limits of application of the filtration equation and reasons for these limits.

2. Comparisons should be made between data for natural iron bearing ground waters from Iowa and other parts of the United States and data for synthetic water used in this study.

3. Some work should be done on the application of diatomite filters to various types of surface water supplies. The equation of filtration should be verified for such waters both with and/or without pre-treatment and for various diatomite grades.

4. A study should be made to determine if the degradation of filter aid which takes place in pumps, body feeders, or other equipment has any significant effect on K_3 and K_4 values.

5. A more accurate method of testing for aluminum iron concentration should be devised if future work is done using salts of aluminum.

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